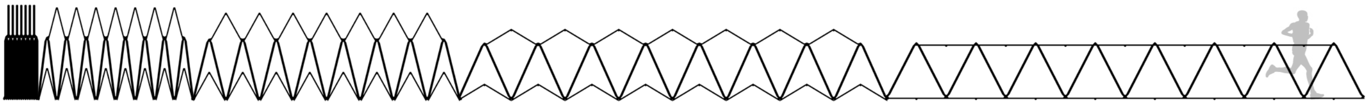
Faculty of Architecture & Build Environment | Delft University of Technology

Graduation Master Thesis
Sustainable Design Graduation Studio

DeMoLi BRIDGE
[designing an emergency connection]



by **Elia Galiouna**

Mentors | Joris Smits and Macel Bilow

MSc in Architecture, Urbanism and Building Sciences
Building Technology
TU Delft, July 2015

DEployable MOdular LIghtnweight

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Graduation Report
July, **2015**

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[ABSTRACT]

Keywords:
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modularity
compacted
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truss
hinged connections

Extreme events, including natural and man-made disasters such as typhoons, floods, tsunamis, earthquakes and terrorist attacks have become the largest destructions around the world over the years. Their impacts can be calamitous devastating entire countries overnight and making millions of people suffer.

Due to the above disasters, bridges are damaged resulting the isolation of residential communities and the inability of delivery emergency relief supplies. In order to provide quick help to disaster areas, an easy-transported, rapid-installed, adaptable to different configurations and cost-efficient temporary bridge becomes critical for transportation of people, food and medical supplies.

This graduation thesis seeks to the design of a **DEployable, MOdular, LIghtweight (DeMoLi) Bridge** as a single-lane "*emergency connection*". The instant connection could be used all over the world reconnecting communities and supporting disaster relief.

DeMoLi is a Warren Pony Truss Bridge, consists of identical prefabricated aluminum elements relying on term of modularity, creating a lightweight structure. The modular segments also facilitate adaptation of the bridge to different spans ranging from 5m to 20m length with load capacity up to 40tons.

Figure 1 | Pakistan floods

The construction process and the final assembly realize off-site (in the factory) and the completed bridge is transported on-site in a compacted form thanks to its deployable capability. Then, it is installed in a limited time and without any special equipment for short term, servicing the emergency needs. After the bridge mission is completed, the bridge is packed and reused in another emergency call. Compared with conventional techniques, this method reduces the demands on launcher providing an integrated solution able to cover a broad spectrum of bridge applications.

Figure 1 | Pakistan Floods [3]
Floods in Pakistan began in late July 2010, when heavy rains stroked the entire country covering one-fifth of its total land area. According to Pakistani government data, the floods directly affected about 20 million people, mostly by destruction of property, livelihood and infrastructure, with a death toll of close to 2,000.
Many bridges were also collapsed. The image illustrates a washed-out bridge, damaged during a flood on Aug. 5, 2010.
Reference to Figure 7.1

[ACKNOWLEDGMENTS]

The graduation process was a really interesting journey through innovative and challenging paths. During these eight months, I learned how to “bridge” theory and practice, starting with a broad research in different fields like bridges, modularity, deployability, etc., and ending up with a final product.
Every “ emergency” matter is a delicate issue, which has to be always dealt with respect and innovativeness in order to be efficient in various levels. Thus, the main challenges were related to the sensibility and the limitations that someone faces, when deals with emergency situations.

I am deeply indebted to my two mentors, *ir. Joris Smits* and *dr.ing. Marcel Bilow*, whose knowledge, understanding and patience, added considerably to my graduate experience.
Firstly, I would like to express my gratitude to my first mentor Joris Smits for the useful comments, remarks and engagement through the process of this master thesis. He was always there to listen, giving me the freedom to explore my own ideas.
A special thanks goes out to my second mentor Marcel Bilow for his excellent

guidance and help, providing me with directions and technical knowledge in a really understandable way. He was really positive, enthusiastic and simultaneously, he had always the way to guide me in a realistic and applicable solution. Moreover, I would like to thank him for his help of the final mock-up.

I must also acknowledge ir. Paul de Ruiter for the provision of the fabrication lab and the 3d printers during the fabrication of the final 3d-printed models.

Most importantly, I would like to thank my family, to whom this dissertation is dedicated to, for their moral support that they have been provided me in my entire life and particularly during these two years of my master school in TUDelft. They were always there encouraging me with their best wishes and love.

Finally, I would like to thank Γιάννη. He was always my constant source of concern, strength, inspiration and assistance all this period, standing by me through the good and bad times.

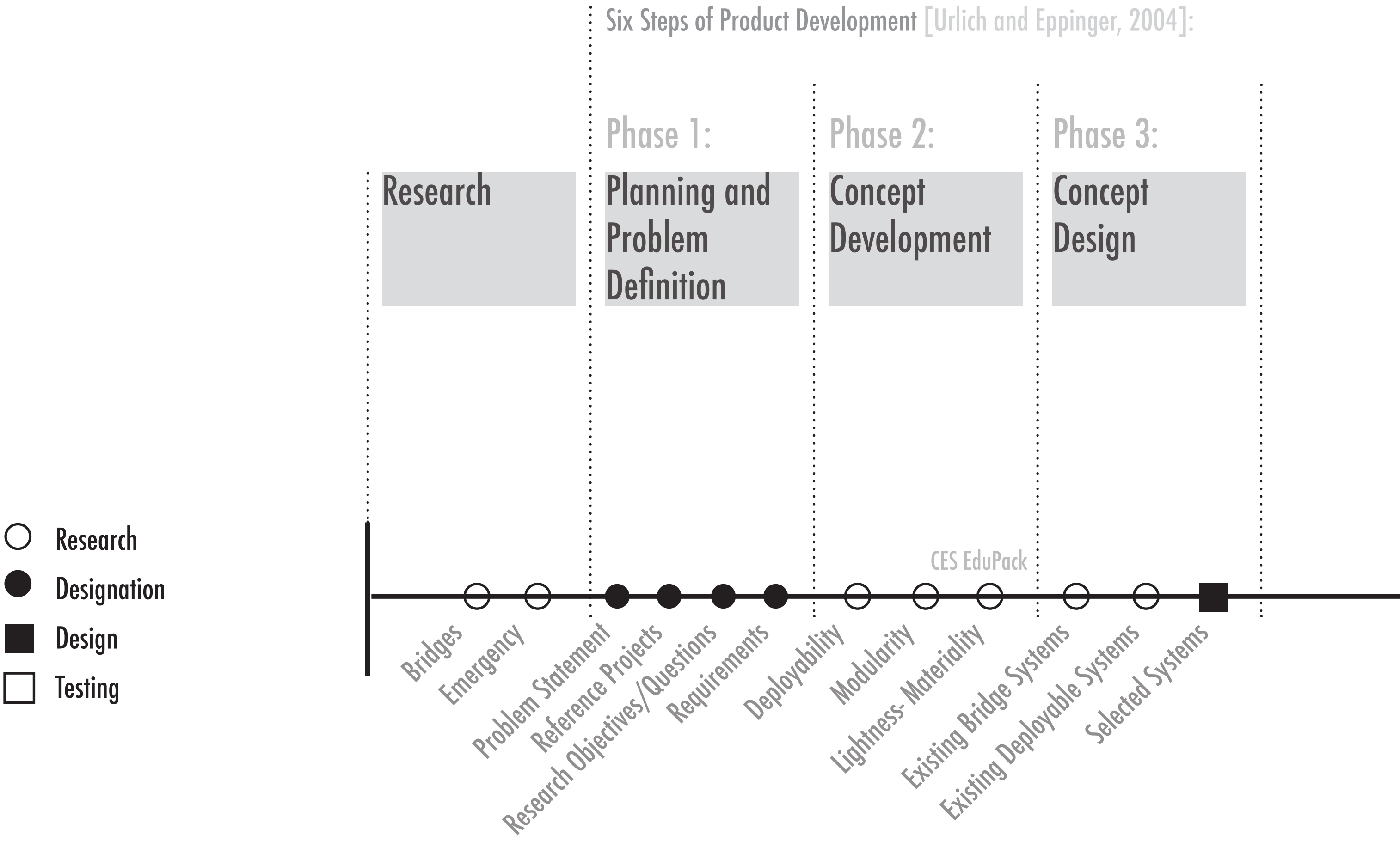

Figure 2| The Six Steps of Product Development Management [1] and its relation to the graduation process

[SCOPE OF RESEARCH]

The following research has been configured as an invention on a novel, emergency, temporary bridge.

The scope of research follows an engineering design process, as a methodical series of steps that engineers use in creating functional products. It is a decision making highly iterative process, in which the basic and engineering sciences are applied to convert resources optimally to meet a stated objective.

Specifically, the proposal framework process of the graduation thesis feeds on the *Six Steps of Product Development Management* according to Urlich and Eppinger [1] and therefore the layout of the whole project is based on the following six phases [Figure 2]:

Phase 1: Planning and Problem Definition

The initiation phase of Planing and Problem Definition is the beginning of the project. In this phase, the basic idea is explored and elaborated. In addition, the project missions statements (problem statements), the research objectives and questions, as well as key assumptions and constraints (requirements) are clari-

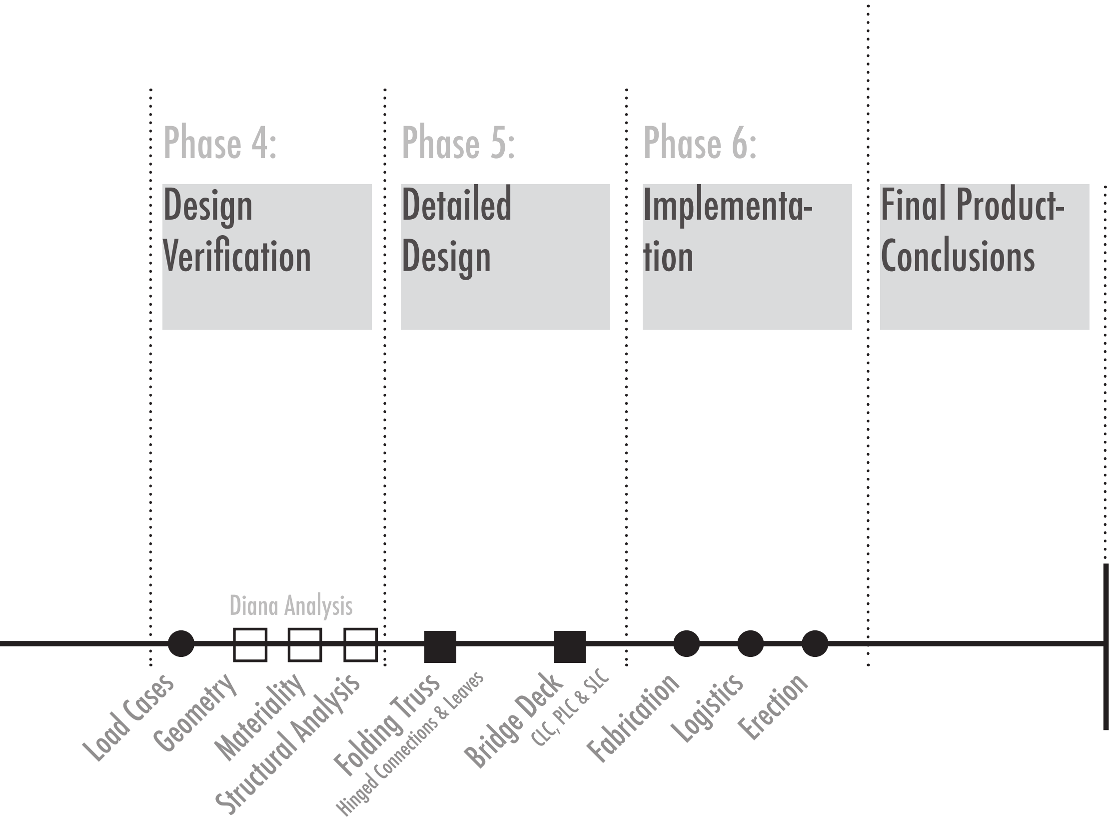

Figure 0.2 | The original six steps of development process according to Urlich, K. and Eppinger, S. [1] are:
0. Planning: project mission statement, target market, business goal, key assumptions, constraints
1. Concept development: identifying customers needs, product specifications, generation, selection, testing and evaluation of one concept
2. System level design: definition of product architecture and the decomposition of the product into subsystems and components
3. Detailed design: specification of materials, geometry and tolerances
4. Testing and refinement
5. Production ramp-up

fied. Finally, six existing emergency bridges, as reference projects, are analyzed, describing their general concepts and pointing out their strong features but also their weak ones, which have to be improved in a new emergency bridge solution.

Phase 2: Concept Development

Concept Development Phase is based on research. Its activities include the selection and deeply analysis of the working principles- design strategies- of the product and the architectural approaches that best meet the project's requirements based on a design through research approach. These decisions are afterwards transformed into technical solutions.

In DeMoLi bridge concept, the applied strategies are: Deployability, Modularity and Lightness. For designation of Lightness, material selection is carried out through CES EduPack software and finally, the selected materials are analyzed.

Phase 3: Concept Design

The Concept Design Phase includes the development of the conceptual product. It involves the intellectual process of developing a research idea into a realistic and appropriate research design.

The conceptual design of a bridge is a step, which the designers must to visualize and imagine the bridge in order to determine its fundamental function and performance before any structural analysis and detailing design are preceded. In DeMoLi solution, this includes consideration of several factors, such as the selection of bridge and deployable system throughout analysis and comparison of existing systems, as well as the description of the selected ones and their application in DeMoLi Bridge.

Consequently, the focus of this phase is two-fold: Firstly, it evaluates the feasibility assessments of the alternatives and secondly, it clearly defines and approves the scope of the project, synthesizing a preliminary design which includes explanation of the system and all the required activities .

Phase 4: Design Verification

This is a product development and refinement phase, which includes extensive testing, validation and optimization in many levels based on several parameters like requirements vs cost.

Normally it involves assembling and testing prototypes through different scale mock-ups and afterwards the implementation of any required changes to the designs. However, in DeMoLi Bridge, Finite Elements Analysis (FEA) is used to refine the geometry and define the materials of the bridge and its individual components through satisfactory numerical calculations that accurately simulate mechanical behaviors such as deflections and stresses.

Starting with the definition of different load cases, proportions and materiality of the truss and the deck panels are finalized and verified. After these, the structural behavior of the final version of the bridge is presented through Diana software.

Phase 5: Detailed Design

Detailed Design or Developed Design Phase, is the process of taking on and developing the approved concept design, establishing the design requirements and transforming them into a final cross-disciplinary design. It provides the links for integrating all the conceptual and preliminary data into a complete, finished digital product. This phase serves the basis for the Implementation.

By the end of Detailed Design process, the proposal solution is dimensionally correct and coordinated, providing a detailed specification for each component and thoroughly description of their interfaces and their functions.

DeMoLi solution is divided into the folding truss, the bridge deck and some extra elements like bearings and access ramp, which are studied and visualized deeply.

Phase 6: Implementation

The Implementation Phase refers to the final process of moving the solution from development status to production one. During this final phase, the project takes its final, realistic shape.

For the purposes of DeMoLi project, implementation is related to a series of steps- plans from fabrication, assembly and transportation until the final installation and the possibility of relocation. All these are presented as a product planning (sequence of plans), which are synonymous with “implementation”.

Finally, this phase involves the visualization of the project results through a series of mock-ups in different scales from 1:20 to 1:2.

Bridge	Location	Country	Date (from 2000- present)	Casualties	Reason
Hoan Bridge	Milwaukee, Wisconsin	United States	13-Dec-00	0 killed, 0 injured	Damage was said to have been caused by extremely cold weather, snow, and heavy amounts of traffic.
Hintze Ribeiro disaster	Entre-os-Rios, Castelo de Paiva	Portugal	5-Mar-01	59 killed	Pillar foundation became compromised due to years of illegal, but permitted sand extraction.
Asagiri footbridge	Akashi, Hyōgo[15]	Japan	21-Jul-01	11 killed, 247 injured	Whilst progressing to a summer firework festival, people stampeded and panicked.
Kadalundi River rail bridge	Kadalundi	India	21-Jul-01	57 killed (all drowned)	
Queen Isabella Causeway	Port Isabel, Texas and South Padre Island, Texas	United States	15-Sep-01	8 killed, 13 survivors	Overloading
I-40 bridge disaster	Webbers Falls, Oklahoma	United States	26-May-02	14 killed	Barge struck one pier of the bridge causing a partial collapse
Rafiganj rail bridge	Rafiganj	India	10-Sep-02	130 killed	Terrorists sabotaged rail bridge, causing crash
Sgt. Aubrey Cosens VC Memorial Bridge,	Latchford, Ontario,	Canada	14-Jan-03	0 killed, 0 injured	Partial failure under load of transport truck during severely cold temperatures.
Kinzua Bridge	Kinzua Bridge State Park, Pennsylvania	United States	21-Jul-03	0 killed	Hit by tornado with 100 mph winds
Igor I. Sikorsky Memorial Bridge	Connecticut	United States	Feb-04	1 killed	Collapse occurred in during demolition of the original 1940 span
Interstate 95 Howard Avenue Overpass	Bridgeport, Connecticut	United States	26-Mar-04	0 killed, 1 injured	Car struck a truck carrying 8,000 US gallons of heating oil, igniting a fire that melted the bridge superstructure.
Big Nickel Road Bridge	Sudbury, Ontario	Canada	7-May-04	0 killed	
C-470 overpass over I-70	Golden, Colorado	United States	15-May-04	3 killed, 0 injured	As part of a construction project, a girder twisted, sagged, and fell onto I-70.
Mungo Bridge[19]		Cameroon	1-Jul-04		
Loncomilla Bridge	near San Javier	Chile	18-Nov-04	0 killed, 8 injured	The structure was not built on rock, but rather on fluvial ground.
Veligonda Railway Bridge		India	29-Oct-05	114 killed	flood washed rail bridge away
Almuñécar motorway bridge	Almuñécar, Province of Granada	Spain	7-Nov-05	6 killed, 3 injured	Part collapsed during construction, reason unknown
Caracas-La Guaira highway, Viaduct	Tacagua	Venezuela	19-Mar-06	0 killed, 0 injured	Landslides
E45 Bridge	Nørresundby	Denmark	25-Apr-06	1 killed	Collapsed during reconstruction due to miscalculation
Yekaterinburg bridge collapse	Yekaterinburg	Russia	6-Sep-06	0 killed, 0 injured	Collapse during construction
Highway 19 overpass at Laval	Laval, Quebec	Canada	30-Sep-06	5 killed, 6 injured	Shear failure due to incorrectly placed rebar, low-quality concrete
Nimule	Nimule	Kenya/Sudan	Oct-06		Struck by truck overloaded with cement
Pedestrian bridge	Bhagalpur	India	Dec-06	More than 30 killed	150-year-old pedestrian bridge (being dismantled) collapsed onto a railway train as it was passing underneath.
Railway bridge	Eziama[*disambiguation needed*], near Aba	Nigeria	Dec-06	Unknown killed	Unknown
Run Pathani Bridge Collapse	80 km (50 miles) east of Karachi,	Pakistan	2006		Collapsed during the 2006 monsoons
	South eastern Guinea	Guinea	Mar-07	65 killed	Bridge collapsed under the weight of a truck packed with passengers and merchandise.
		South Korea	5-Apr-07	5 killed, 7 injured	parts of a bridge collapses during construction
MacArthur Maze	Oakland, California	United States	29-Apr-07	1 injured in crash, 0 from collapse	Tanker truck crash and explosion, resulting fire softened steel sections of flyover causing them to collapse.
Highway 325 Bridge	Foshan, Guangdong	China	15-Jun-07	8 killed, unknown injured	Struck by vessel
Gosford Culvert washaway		Australia	8-Jul-07	5 killed (all drowned)	Culvert collapse
Minneapolis I-35W bridge	Minneapolis, Minnesota	United States	1-Aug-07	13 killed, 145 injured	Increased concrete surfacing load, and weight of construction supplies/equipment caused this collapse.
Tuo River bridge	Fenghuang, Hunan	China	13-Aug-07	34 killed, 22 injured	Local contractors often opt for shoddy materials to cut costs and use migrant laborers with little or no safety training.
Harp Road bridge	Oakville, Washington	United States	15-Aug-07	0 killed, 0 injured	Collapsed under weight of a truck hauling an excavator.
Water bridge	Taiyuan, Shanxi province	China	16-Aug-07	unknown	180t vehicle overloaded bridge designed for 20t
Shershah Bridge	Karachi	Pakistan	1-Sep-07	5 killed, 2 injured	Investigation underway
Flyover bridge	Punjagutta, Hyderabad, Andhra Pradesh	India	9-Sep-07	15-30 killed	during construction
Cần Thơ Bridge	Cần Thơ	Vietnam	26-Sep-07	36-60 killed, hundreds injured	Investigation underway
Chhinchu suspension bridge	Nepalgunj, Birendranagar	Nepal	25-Dec-07	19 killed, 15 missing	Overcrowded suspension bridge collapsed
Jintang Bridge	Ningbo, Zhejiang province	China	27-Mar-08	4 Killed, 0 Injured	Ship hit lower support structure of bridge.
The Cedar Rapids and Iowa City Railway (CRANDIC) bridge	Cedar Rapids, Iowa	United States	12-Jun-08	0 killed, 0 injured	during June 2008 Midwest Floods
Road bridge	Studénka	Czech Republic	8-Aug-08	8 killed, 70 injured	Train crashed into a road bridge over the railway under construction.

Somerton Bridge	Somerton, NSW	Australia	8-Dec-08	None	Heavy flooding
Devonshire Street pedestrian bridge	Maitland NSW	Australia	5-Mar-09	0 killed, 4 injured (Car & Truck Drivers)	Over Sized truck clipping main span
Bridge on SS9 over River Po	Piacenza	Italy	30-Apr-09	0 killed, 1 injured	Collapsed due to flood of River Po
9 Mile Road Bridge at I-75	Hazel Park, Michigan	United States	15-Jul-09	0 killed, 1 injured	collapsed due to tanker accident
Malahide Viaduct	Broadmeadow – 13 km (8.1 miles) north of Dublin	Ireland	21-Aug-09		
Tarcoles Bridge	Orotina	Costa Rica	22-Oct-09	5 killed, 30 injured	Overload by heavy trucks and dead loads (water pipes).
San Francisco – Oakland Bay Bridge	Connects San Francisco and Oakland, California	United States	27-Oct-09	0 killed, 1 injury	Two tension rods and a crossbeam from a recently installed repair collapsed.
Railway Bridge RDG1 48 over the River Crane	Feltham	England	14-Nov-09	No injuries .	Undermined by scour from river.
Northside Bridge, Workington	Cumbria	England	21-Nov-09	1 policeman killed	Very intense rainfall produced extreme river loads that overwhelmed all the bridges.
Navvies Footbridge, Workington	Cumbria	England	21-Nov-09	1 policeman killed	Very intense rainfall produced extreme river loads that overwhelmed all the bridges.
Camerton Footbridge, Camerton	Cumbria	England	21-Nov-09	1 policeman killed	Very intense rainfall produced extreme river loads that overwhelmed all the bridges.
Memorial Gardens footbridge, Cockermouth	Cumbria	England	21-Nov-09	1 policeman killed	Very intense rainfall produced extreme river loads that overwhelmed all the bridges.
Low Lorton Bridge, Little Braithwaite Bridge	Cumbria	England	21-Nov-09	1 policeman killed	Very intense rainfall produced extreme river loads that overwhelmed all the bridges.
Kota Chambal Bridge	Kota, Rajasthan	India	25-Dec-09	9 killed, 45 missing[41]	
Myllysilta	Turku	Finland	6-Mar-10	0 killed, 0 injured	Bridge bent 143 centimetres (56 in) due to structural failures of both piers
Gungahlin Drive Extension bridge	Canberra	Australia	14-Aug-10	15 workers injured	Under investigation
Guaiba's Bridge (BR-290)	Porto Alegre, Rio Grande do Sul	Brazil	1-Oct-10	0 killed, 0 injured	Braking system (electrical) failure stuck the main span 9 meters.
Overbridge over Chengdu-Kunming Freeway	Zigong	China	1-Jul-11		Truck crashed against concrete support pillar
Gongguan Bridge	Wuyishan, Fujian	China	14-Jul-11	1 Killed, 22 Injured	Overloading
No. 3 Qiantang River Bridge over Qiantang River	Hangzhou, Zhejiang province	China	15-Jul-11	0 Killed, 1 Injured	Overloading
Baihe Bridge in Huairou district	Beijing	China	19-Jul-11	0 Killed, 0 Injured	Bridge designed for max. 46 tonne vehicles, truck overloaded with 160 tons of sand.

***Bridges** are links; that connect people and communities.*

[Blockey, 2010]

Kutai Kartanegara Bridge	Tenggarong, East Kalimantan	Indonesia	26-Nov-11	20 Killed, 40 Injured (33 missing)	Human error. Bridge collapsed while workers repaired a cable. (Under investigation)
Eggner Ferry Bridge over the Tennessee River	Kentucky	United States	27-Jan-12	0 Killed, 0 Injured	The MV Delta Mariner struck the bottom portion of a span of the bridge when travelling in the incorrect channel of the river.
Jernbanebroen over Limfjorden	Aalborg	Denmark	28-Mar-12	none	ship collision
Yangmingtan Bridge over the Songhua River	Harbin	China	24-Aug-12	3 Killed, 5 Injured	Overloading; usage of unsuitable building material (suspected)
Bridge under construction for road E6 at Lade/Leangen	Trondheim	Norway	8-May-13	2 killed	Bridge collapsed under construction
I-5 Skagit River Bridge collapse	Mount Vernon, Washington	United States	23-May-13	0 Killed, 3 Injured	Oversized semi-truck load carrying drilling equipment from Alberta clipped top steel girder causing bridge collapse.
Scott City roadway bridge	Scott City, Missouri	United States	25-May-13	7 injured	Rail crash.
Wanup train bridge	Sudbury, Ontario	Canada	2-Jun-13	0 killed, 0 injured	Train trestle over the Wanapitei River near Sudbury, Ontario was struck by derailed railcar
CPR Bonnybrook Bridge	Calgary, Alberta	Canada	27-Jun-13	0 killed, 0 injured	Partial pier collapse due to scouring from flood event of the Bow River
Belo Horizonte overpass collapse	Belo Horizonte, Brazil	Brazil	3-Jul-14	2 killed, 22 injured	To be determined
Hopple Street Overpass over I-75 Southbound	Cincinnati, Ohio	United States	19-Jan-15	1 killed, 0 injured	Old Northbound Hopple Street offramp totally collapsed onto roadway below during demolition
Plaka Bridge	Plaka-Raftaneon, Epirus	Greece	1-Feb-15	0 killed, 0 injured	Flash flood ripped foundations from the riverbanks
Skjeggestad Bridge	Holmestrand	Norway	2-Feb-15	0 killed, 0 injured	Partial pier displacement due to landslide.

Figure 3 | List of the most famus Bridge Failures from 2000-present [2]

[CONTENTS]

1.

Planning and Problem Definition

The initiation phase of Planing and Problem Definition is the beginning of the project. In this phase, the basic idea is explored and elaborated. In addition, the project missions statements (problem statements), the research objectives and questions, as well as key assumptions and constraints (requirements) are clarified. Finally, six existing emergency bridges, as reference projects, are analyzed, describing their general concepts and pointing out their strong features but also their weak ones, which have to be improved in a new emergency bridge solution.

floods

territory attack

wrong calculations

fire

tornado

earthquakes

1.1 Problem Statement

“Mayday, Mayday, Mayday- Bridge down”.

Every year, severe floods, typhoons, storms, hurricanes, landslides and other natural disasters but also explosions and terrorist attacks have been dramatically increasing in both number and intensity, causing havoc in communities and immense suffering for millions of people around the globe. Damages and casualty percentages have reached record levels every year during the last decade. The number of people affected by natural disasters is alarmingly high, estimated in the hundreds of millions.

When disaster strikes, whether natural or man-made, urgent priorities, such as evacuation of habitants, care of injured, provision of food and water are vitally important but a lot of times can be severely hampered and infeasible, especially in cases that transportation networks are interrupted due to bridges collapse[1] [Figure 3]. This results to the inability of relief workers and supplies to reach stricken areas.

We know that we cannot underestimate the importance of emergency planning. If an earthquake or terrorist attack hits, we won’t necessarily have advance alerts or opportunities to double- and triple-check our plans and therefore we have to

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1. In the broadest sense, failure of a bridge occurs whenever it is unable properly to fulfill its function, for instance to carry the primary loads across an opening.
Several types of uncertainties can be identified that cause bridge failures like natural randomness actions, material properties, geometric data, statistical uncertainties due to limited available data, uncertainties of resistance and load effect models due to simplifications of actual conditions, gross error in design during execution and use, lack of knowledge concerning behavior of new materials and actions in actual conditions etc. [1.21]

Figure 1.1 | Tacoma Bridge, Washington

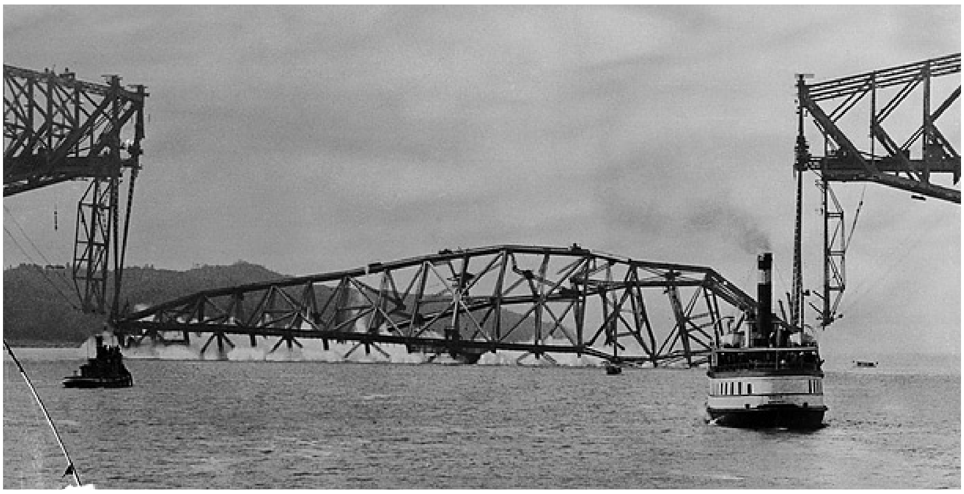


Figure 1.2 | Quebec Bridge, Canada

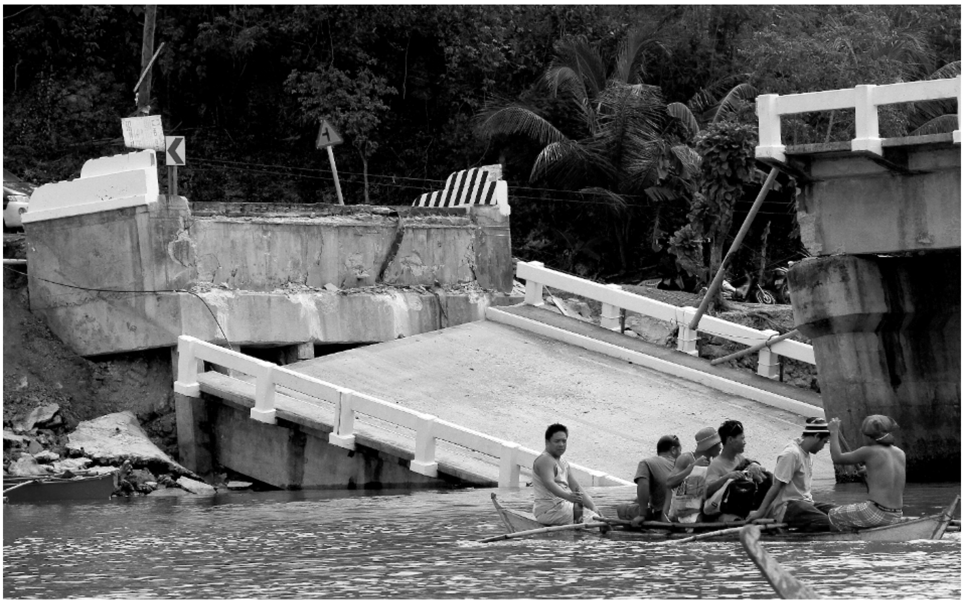


Figure 1.3 | Devastation in the Philippines

Bridge Failures

Figure 1.1 | Tacoma Bridge [1.18]

Tacoma Narrows Bridge, was a suspension bridge in the U.S. state of Washington that spanned the Tacoma Narrows strait of Puget Sound between Tacoma and the Kitsap Peninsula. It opened to traffic on July 1, 1940, and dramatically collapsed on November 7 of the same year because of a physical phenomenon known as aeroelastic flutter. No human life was lost in the collapse of the bridge. Tubby, a black male cocker spaniel, was the only fatality of the Tacoma Narrows Bridge disaster.

Leonard Coatsworth, a Tacoma News Tribune editor, was the last person to drive on the bridge: *"Just as I drove past the towers, the bridge began to sway violently from side to side. Before I realized it, the tilt became so violent that I lost control of the car. I jammed on the brakes and got out, only to be thrown onto my face against the curb [...] Around me I could hear concrete cracking. The car itself began to slide from side to side of the roadway[...]"*

On the final day the bridge oscillated for some hours in a relatively usually vertical mode. The wind velocity was measured as 68kph. Suddenly, the motion changed to a torsional mode and became violent. Within 8 to 10 min, there was evidence of damage to lampposts and to the concrete side-walks. The subsequence collapse was rapid with progressive failure either of the suspenders or of their connectors to the deck and finally a large portion of the deck of the main span fell into the stream. [1.18]

Figure 1.2 | Quebec Bridge, Canada [1.19]

The Quebec Bridge is a road, rail and pedestrian bridge across the lower Saint Lawrence River to the west of Quebec City in Canada with two main spans of 518m. It is a cantilever truss bridge. The project failed twice, at the cost of 95 lives, and took over 30 years to complete. Due to a design flaw the actual weight of the bridge was heavier than its carrying capacity, which caused the double collapse, once in 1907 and then in 1916.

Figure 1.3 | Devastation in the Philippines [1.20]

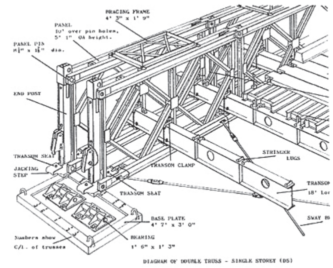
Bohol Island Earthquake, October 2013

The earthquake of 7.2 magnitude struck the central Philippines. It knocked out bridges and roads across the island of Bohol, and displaced more than 350,000 people.

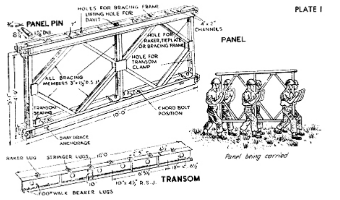
The figure shows the residents using an outrigger (small canoes) to cross a river near a damaged bridge on the popular tourist island of Bohol. *"The bridge into Antequera has collapsed, so we had to cross the river on a small wooden boat, a "bumboat" as it is known in South-East Asia."*

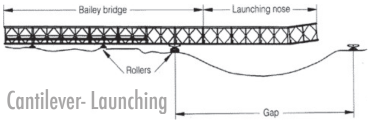
large number
small components
hand erection
=

simplicity
flexibility
cost-efficient
[time-consuming, effort]



The maximum modular panel





Cantilever- Launching

Figure 1.4 | Bailey Bridge (or Heavy Girder Bridge) [1.5 and 1.7]

Whilst working in the British War Office during World War II (WWII), civil servant Donald Bailey had an idea for a radical new bridge. His design for a modular, light but strong and very versatile steel bridge system proved to be one of the greatest inventions of WWII and was destined to play a significant part in the allied victory.

The subsequently named Bailey Bridge was adopted as the standard Military Bridge in 1941 and was used extensively throughout the European campaign.

By 1947, some 2,000 Bailey Bridges had been built with more than 1,500 bridges being constructed in North West Europe alone.

The Bailey Bridge was further credited with hastening the end of the war. As Field Marshal Bernard Montgomery wrote in 1947:"*Bailey Bridging made an immense contribution towards ending World War II. As far as my own operations were concerned, I could never have maintained the speed and tempo of forward movement without large supplies of Bailey Bridging.*"

The contribution of the Bailey Bridge was such that Donald Bailey was awarded an OBE in 1943 and knighted in 1946 in recognition of his outstanding contribution.

Figure 1.4 | Bailey Bridge (or Heavy Girder Bridge)

arm ourselves with the necessary equipment. Part of the plan is the design and construction of emergency bridges able to reconnect communities by providing an uninterrupted access to the effected area and reestablishing them[2].

1.2 Reference Projects

In an emergency case, the conventional bridge construction techniques, which are fixed and massive structures, based on all-in-one communications management unit (integral design), made on-site in a slow construction process and required large transport vehicles and specialized workers, are not desirable options. The design must follow the rules of emergency, which in contrast to the above description are based on off-site fabrication, quick and easy transportation and installation process without any specialized equipment.

The most common emergency bridges are referred to military purposes. The military bridges are classified in three types according to the mission that they serve [1.4]. The first mission type is the Assault Mission Bridges, which are characterized by their high mobility and serviceability, due to their need to support combat forces in hostile environments. Bridges deployed in Assault missions must be readily transportable, minimizing the logistic burden for storage, inspection and transportation. They must be constructed and dismantled repeatedly in the field in a matter of minutes with guaranteed access to one side of the gap and without exposure of crew. Hence, they made up of few modular, large and heavy components, precluding manual construction, which are launched using variety

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[2] Nowadays, in most of the above circumstances, rescue teams and locals built really temporary and unsafe connections made of tree trunks or worthless objects that they can found around. Moreover, many times, international aids help the affected areas by providing helicopters and boats. However, these solutions are not always possible, effective or safe.

Figure 1.5 | Armored Vehicle- Launched Bridge (AVLB)

of advanced and fully automated construction technologies, like remote vehicle control, robotic, improved sensors, video imagery and laser range-finders, etc. [1.2]

The second type of bringing mission, termed as Tactile Mission, provides a semi-permanent solution to quick cross-gap. Deployed under these missions typically require more resources, site preparation and time than the Assault Bridges. The Tactical Bridge typically replaces the Assault Bridge, once control of an area is obtained. Tactical Bridges are designed to carry higher volumes of wheeled and tracked traffic and be left in place for longer periods of time.

The third type is called Line of Communication Mission. In this case, the bridges are more permanent. This category uses large numbers of small components assembled and dismantled by hand requiring the longest amount of time and the greatest number of resources to deploy.

The above classification and case studies of previews and existing designs show that the emergency bridges are using neither large number of small components assembled and dismantled by hand, such as the Bailey bridge [Figure 1.4], nor fewer and larger components (and consequently heavier) whose motions are synchronized by electronic means reducing build time and manpower but increasing the cost. Almost all the military emergency bridges fall in the second category. An example is the AVLB Bridge as shown in Figure 1.5.

The above two categories are investing:

a. Either in *simplicity* during transportation and erection (by handy pieces and without any special equipment and technologies during launching), *flexibility* by covering a variety of applications and finally *economy,*

b. Or in time (*speed*) creating structures that are able to fast install in just few

small number
large- heavy components
special mechanisms
=

speed

[standard span, knowledge, high-tech, expensive]

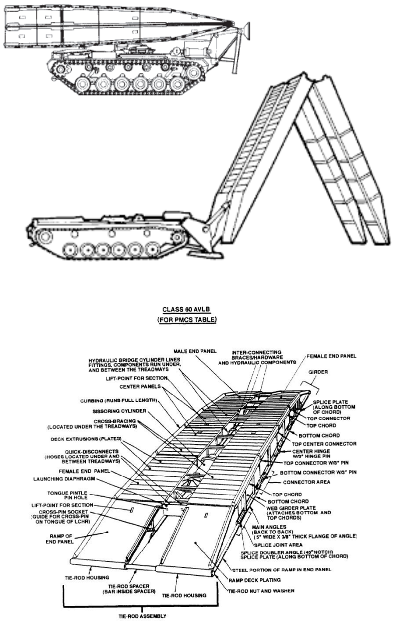

Figure 1.5| Armored Vehicle- Launched Bridge (AVLB) [1.10 and 1.12]

The Armored Vehicle-Launched Bridge (AVLB) was introduced in 1987.

This combat engineering vehicle was developed by General Dynamics to replace the previous M48 AVLB. It is designed to launch bridge for tanks and wheeled combat vehicles across trenches and water obstacles in combat conditions.

A total of 400 armored bridgelayers were built. It is in service with the US Army and Marines. Export operators are Egypt, Iran, Israel, Pakistan, Singapore and Spain.

minutes.
So far, the concept of an emergency bridge is distinguished to rapid assembly or to high flexibility and mobility with small units and a more cost-efficient solution.

Subsequently, six reference projects from existing, previews or conceptual emergency bridge solutions are analyzed, pointing out their strong and weak points. These projects belong to the three former categories of military bridges or to hybrid approaches.
The first two examples are the Baily Bridge, which it was developed during World War II and its updated version of Mabey Compact 200 made by the UK Mabey Bridge Company. Both of them belong to the Line of Communication mission.
Then, the AVLB and BR90 Bridge are two examples of assault and tactile mission.
The last two projects are recent examples. The ARCS system by ATA Engineering was started in 2012 and it is still under development, while the AIR-Bridge is a project funded by CERCE under the Prova't 2011 and it was developed from January 2012 to December 2013 by two Spanish entities (CIMNE, BuildAir).

1.2.1 Bailey Bridge

The Bailey bridge is a type of portable, prefabricated, truss bridge, which it was developed during World War II (in 1940s) for military use and lies in Line of Communication mission [Figure 1.4]. After the war, Bailey Bridges were used extensively throughout Europe to rebuild its infrastructure and many examples can still be found around the globe. [1.5]
Donald Bailey was the civil engineer who invested Bailey Bridge System. His idea was to provide temporary bridges, able to carry heavy tanks, that could be quickly erected under difficult conditions and applications. [1.5]
All the used components were standardized and interchangeable, highly adaptable and flexible. The bridging equipment was indeed a hodge-podge of parts, able to be transported on a 3-tonne truck, handled by up to six men[3] and finally erected with only common (but very ingenious) hand-tools like ropes, pulleys, jacks, and hammers. [1.22]
Connections were pinned, bolted, or clamped with no welding. In this way, disassembly was also straightforward.
The components were put together in a number of configurations to accommodate a range of span and capacity requirements; e.g. panels were connected together in two or three stores to make the bridge stronger and capable of carrying heavier loads.
The principle of the bridge was simple. Pin-connecting lugged on each corner permitted connection of other such panels for any desired length as well as sideward or upward for added carrying capacity. The vital part was the lattice-work panel which was carried ready assembled, and in fact it is strongly welded. [1.8]
A Bailey bridge consisted of four elements: the panels, the decking, the bearings, and the fixings. The panels were prefabricated welded steel cross-braced rectangles 3m long. The deck was made of steel I-section cross beams or transoms clamped onto the panels to hold them together. Smaller beams or stringers spanned between the transoms. Finally, the deck was surfaced with timber or steel panels.
It was also the method of “cantilever launching” that made the Bailey bridge so novel. Firstly, a “nose” was built. Each 10feet section was built up on shore, complete with roadway, and then the section was assembled on special well-greased rollers, almost to the point of balance. The properly counter-balanced bridge, was slid across the gap, by man-power(!). Afterwards, the next section was added and the bridge was pushed forward and another section was built behind it, pushed and so on (during this process the “nose” was hanging over the gap). For the final

---

[3] The maximum dimensions of modular panels are 3.0m long, 1.5m height and 260kg. [1.8]

Figure 1.6 | Mabey Compact 200 Bridge

step, extra counterweight was used. Since the bridge reached its final position the nose, the counterweight and the rollers were removed, the whole structure was jacked down to spread footers, so that the bridge can be locked in position and the ramps were installed. [1.8]

Most bridges can be assembled in a matter of days by a small crew. The number of men and vehicles used on construction varies with the size and speed required. But forty men can construct a complete bridge. [1.8]

The advantages of Bailey's design were:

1. Its *simplicity* during construction, which enabled mass production.
2. Its *transportability*, without the need of special transportation vehicles. Every part fits into a 3-ton lorry, and a small group of these vehicles can move everything required for a complete bridge.
3. Its *flexibility* because of the way that length and strength can be varied[4]. The Bailey bridge could cross any kind of gap. Without supports or pontoons, the Bailey spanned a gap of up to 240 ft (73m)[5]. The bridge was constructed with single panels and single tiers so as to take moderately heavy traffic immediately. Additional panels and tiers were achieved greater loading capacity.
4. Its *replacement capacity*. If the bridge is damaged by shells or bombs, the damaged section were easily removed and a new one inserted.

Bailey Bridge, was a great invention during the second World War. Although its

large number
small components
hand erection
=

simplicity
flexibility
[time-consuming, effort]

part of the mabey family

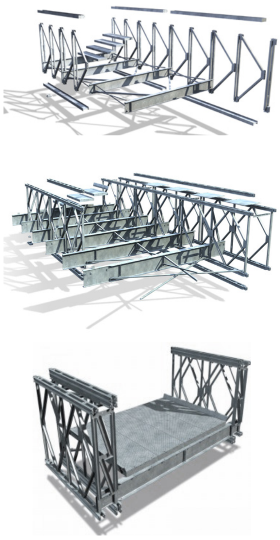

Figure 1.7 | Mabey Compact 200 Bridge [1.6]

The Mabey Universal Bridge System is an advanced version of the original Bailey bridge design. Mabey Bridge recognized that the original Bailey design was capable of further development to broaden its application potential further. The result of this work was the Mabey Super Bailey Bridge system which eliminated some of the original design's limitations. Following the success of the Mabey Super Bailey Bridge, the company continued to invest in an extensive program of Research and Development.

Today, Mabey Bridge continues to invest significantly allows the company to offer a broad selection of bridging solutions to worldwide markets.

According to Mabey website [1.6]: *The Mabey Compact 200 Bridge system is the most widely used modular bridge system in the world.*

Various decking systems can be supplied to suit the international loading standards required for the project.

All main structural components are hot-dip galvanised steel to ensure a long life with minimal maintenance.

Finally, Mabey Bridge maintains stocks of Compact 200 bridging to enable the company to react to emergency situations in the shortest possible times. These components can be air freighted to sites around the World to minimize response times.

---

[4] It is not surprising that Field-Marshal Montgomery said that: "There is never enough Bailey bridging. This bridge is quite the best thing in that line we have ever had; it does everything we want!"[1.5]

[5] Using the supports of a bridge that has been destroyed, or pontoons, the bridge can cover almost any distance. The longest Bailey bridge so far constructed is believed to be the 1,200 ft (365m) over the Sangro River in Italy, a triumph of military engineering. The longest floating Bailey bridge (1,096 ft.- 335m) was thrown over the Chindwin in Burma in December 1944. [1.8]

general concept is until today really innovative, especially regarding the flexibility that offers and its novel launching process, it presents some drawbacks that could be avoided regarding the current technologies and must be improved in a new version of emergency bridge. The first disadvantage lies to the erection time as well as the effort that was needed by a large number of crew (powerful crew). Another weak point is the weight of the structure[6]. Due to the material that was used (steel) the structure became heavy making the erection and transportation processes even more difficult and time-consuming.

1.2.2 Mabey Compact 200 Bridge

Mabey Compact 200 Bridges are steel, modular, portable, prefabricated truss bridges for temporary and permanent infrastructure applications in cities, disaster stricken areas and remote regions, which are invested by the Mabey Bridge Company [Figure 1.6].

Their general concept has a heritage stretching back to the original Bailey bridge system and consequently, they also consist of a large number of small, standard and pre-engineered components.

Bridges can be erected using cranes for assembly and installation, however on sites where crane availability is restricted, assembly is realized by hand through the cantilever launch method, just like the Bailey Bridge.

The Mabey Compact 200 Bridge system uses 3.048m (10ft) long panels braced together to form modular side trusses for the formation of either a single or two-lane crossing[7]. Transverse steel beams span between the side trusses and carry a proprietary bolted Mabey steel deck system.

The main benefit of this type of bridge is its flexibility due to its modular approach, in order to be able to cover different spans and needs through a broad range of solutions all over the world. The maximum available span is 70m (230ft).

Due to the fact that Mabey Compact 200 Bridge refers also to more permanent applications the erection time is not its priority. The effort and the time that are needed for a 24m length Mabey Compact 200 are 4 day by 7 workers, which is considered as a fast solution compared with assembled time of conventional bridges but as a slow one in the case of an emergency. The time-consuming results from the large number of components that must be assembled. Furthermore, since there is a large number of components that must be assembled, special knowledge is needed. Finally, although it is an advanced version of the original Bailey Bridge, the material that it uses is also steel and consequently the final structure is also heavy[8]. To sum up the disadvantages in this solutions are again the time, the effort and the knowledge that are needed.

1.2.3 Armored Vehicle-Launched Bridge (AVLB)

An Armored Vehicle-Launched Bridge (AVLB) is a combat support vehicle, designed to assist military in rapidly transportation of tanks and other armored fighting vehicles across rivers and it belongs to the assault mission category. In general, it is a tracked vehicle converted from a tank chassis to carry a folding metal bridge instead of weapons [1.10]. The bridge layer unfolds and launches its cargo, providing a ready-made bridge across the obstacle in only few minutes.

On the vehicle, the bridge is carried folded and launched over the front hydraulically. When the vehicle has reached the space to be bridged, the bridge is raised into the vertical, unfolded and then lowered into the place. Once the span has been put in place, the AVLB vehicle detaches from the bridge, and moves aside to allow traffic to pass. Since all of the vehicles have crossed, it crosses the bridge

---

[6] A clear span, single lane bridge, 35m length- 87tons. [1.8]

[7] Standard roadway widths of 3.15m (single lane), 4.2m (extra wide single lane) and 7.35m (2 lanes) are available. [1.6]

[8] A clear span, single lane bridge, 35m length- 55tons, 32tons less than Bailey Bridge. [1.6]

Figure 1.7 | BR90

small number
large- heavy components
special mechanisms
=

speed

[standard span, knowledge, high-tech, expensive]

Figure 1.7 | BR90 [1.16]
A 12-man team put in a place a 36-meter long bridge across a strategic stretch of the Nahr-e-Bughra canal near the town of Shaheed in northern Nad-e-Ali. The town and canal were both seized by British and Afghan forces as part of Operation Moshtarak.

itself and reattaches to the bridge on the other side. Then, it retracts the span ready to move off again. A similar procedure can be employed to allow crossings of small chasms or similar obstructions. [Figure 1.5]
The launching procedure takes about three minutes, while the recovery time is between 10 and 60 minutes, depending on terrain conditions [1.12].
This combat engineering vehicle has a crew of two, including commander and operator [1.11].
AVLBs can carry bridges of 60 feet (19 meters) and can span a gap up to 18 m. The unfolded bridge is capable of supporting tracked and wheeled vehicles with a military load bearing capacity up to Class 70[9] [1.10].
The bridge and vehicle total weight is approximately 58tons. The scissors-type bridge of 15m weights over 13tons and is made of aluminum [1.2]. The launcher is mounted as an integral part of the chassis.

1.2.4 BR90

BR90, know as Bridging for the Nineties, is the longest and fastest tactical available bridging system [Figure 1.7]. The all-encompassing design offers rapid replacement of civilian infrastructure in combat and peacetime disaster relief. Up to 44m of bridge can be built using this system. [1.13]
This system is based on a standard 32m span, which is carried, launched and recovered from 3 specialist vehicles: one Automated Bridge Launching Equipment (ABLE) and two Bridging Vehicles (BV).
The Automotive Bridge Launching Equipment (ABLE) proposes a specially designed vehicle equipped with a crane and an assembly platform where the launching rail could be constructed launched from the vehicle. Hence, the ABLE vehicle carries the launch and recovery equipment as well as some bridge parts. The launching rail is leveled over the gap and bridge sections are added, booming them across, until the gap has been spanned. The launch rail is then recovered and bridge is done. The two Bridging Vehicles (BV) carry the remainder of the bridge set. Each BV has a large flatbed body with a crane permanently mounted behind the vehicle cab. Each BV normally carries either the left or the right side (although they are identical), which are used to lift and sling the panels of the bridge onto rollers mounted within the ABLE launch vehicle, where they are pinned together by hand to form the two continuous trackways. [1.2]
They are then added during the build using the cranes. [1.15]
To build the bridge, the ABLE builds its launch rail across the gap and the BVs park either side of it, and, simultaneously, pass the bridge panels onto the ABLEs building platform. When the bridge is at the required length, it is lowered onto

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[9] The AVLB spans a 15m gap for Military Load Class (MLC) 70, and spans an 18m gap for MLC 60. [1.11]

the ground and disconnected from the launch rail. Finally, centerpieces are fitted and also curbs [1.14].

This system relies heavily on mechanization to supplement manual construction. Each panel, made of advanced aluminum alloy, weights about two tons and the erection time is approximately 30 minutes by a team of ten men.

The main disadvantages of the latter two examples are the high-tech erection mechanisms, the large and specified vehicles for transportation that booms the cost in really high levels[10] but also their span standardization.

1.2.4 ARCS Bridge

ARCS is an adaptive (modular), lightweight, temporary bridge for rapid deployment, developed by ATA Engineering, Inc. under an SBIR grant from the U.S. Army's Tank Automotive Research, Development and Engineering Center (TARDEC). The ARCS solution provides a common, highly portable and temporary gap-crossing solution with the versatility to meet the requirements of assault, tactical, and line-of-communication missions. [Figure 1.8]

ARCS can be deployed rapidly while remaining adaptable to different gap widths and loads fulfilling the need for a “bridge-in-a-box”. A complete deployment-ready 24meter bridge can be transported to the site inside a standard intermodal shipping container[11]. The bridge can be easily handled by forklift, allowing quick loading of an entire bridge system into a shipping container for transport of a complete bridge system by road, rail, sea, or air, and its lightweight construction minimizes the associated transportation resources.

The approach of the ARCS system utilizes modular construction extensively to deliver a quickly installed bridge with a broad range of load and span options through on-demand hardware configuration. A modular truss unit serves as the building block of the bridge, providing both the roadway and structural support. Repeated module instances are assembled to form bridge segments of a given strength and desired roadway width, which are in turn connected to achieve a customizable bridge span. The user is thereby able to tailor the bridge span and load capacity to the circumstances of a particular crossing.

The ARCS bridge system is formed from a tied arch in which truss modules are interleaved to simultaneously achieve high strength and enable folding of the bridge into a compact package for efficient transportation and storage. The resulting bridge system is engineered to accommodate military or commercial vehicles weighing up to 100 tons in crossing spans of 8 to 12 meters (25 to 40 feet). Its adaptive design allows the bridge span to be further increased in exchange for reduced vehicle load capacity.

The advantages of this solution are:

1. *Variable span length*: Assembly of different bridge spans in increments of 2 meters. For example, the system is designed to accommodate crossing by a Military Load Classification (MLC) 45 vehicles across gaps ranging from 8 to 32 meters simply by varying the number of segments from 4 to 16. The system likewise enables crossing by heavier vehicles, potentially up to MLC100, at reduced maximum spans.
2. *Adaptable load capacity*: Accommodation of higher load categories by adding modules to widen and strengthen segments. Conversely, applications involving more lightweight vehicles can avoid the cost and weight of excess structural capability.
3. *Inventory control*: Modules and segments can be warehoused and configured as required for a specific campaign.
4. *Manufacturing efficiency*: Production can be streamlined around the design of

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[10] For an AVLB of 18meters, the price rises at 800.000euro. [1.12]

[11] A complete, deployment-ready 24 meter (80 foot) bridge fits in an ISO standard 40 foot intermodal shipping container. [1.23]

Figure 1.8| ARCS Bridge

small components
compact
=

simplicity
flexibility
[time-consuming, effort, road bridge]

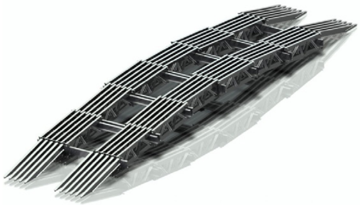

Figure 1.8| ARCS Bridge [1.23]
"Bridge-in-a-box"
The prototype that resulted from this effort is a 12.80m (42-foot), 6000kg (13200lb) demonstration bridge constructed from aluminum and designed to handle loads in excess of 30 tons. The bridge was composed of six segments constructed from interleaved aluminum modules. [1.4]

the repeated bridge module instead of a catalog of components.
5. *Repair/maintenance logistics:* A damaged module or segment can be switched out easily.
6. *Shipping convenience*: A complete 24 m bridge fits in an ISO 40 ft container for road, rail, and sea transportation and in a C-130 cargo bay for air transportation.
Beyond the various advantages, there are also certain disadvantages. The first and main one results from the launching process. The erection through the adjustment of these heavy parts[12] (each segment weights 550kg) that have to be accurate placed in different and seems hard. Another drawback, the general form of the structure, which has no railing or a solid deck panel that makes it unsafe and unsuitable for pedestrian use.

1.2.5 AIR- Bridge

The AIR-Bridge [Figure 1.9] is an inflatable, ultra-lightweight, fast-deployable bridge for surface transport vehicles, which utilizes low-pressurized, air-filled beams as the primary load-bearing spanning members [1.17].
Its principle is based on:
Tensairity= Tension + Air + Integrity
The main objective of the project was to develop, build, validate and subsequently exploit a unique air-bridge for surface transport vehicles that utilizes structural, high performance composite fabric, computer controlled, pressurized air-filled beams as the primary load-bearing structural spanning members.
The AIR-Bridge is a lightweight, low pressure bridge formed by two air-filled beams connected by an upper deck of metallic, composite or hybrid material.

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[12] Heavy structure: 11(segments) x 550kg= 6T (12m) [1.4]

Specifically, the bridge consists of two inflatable beams 14m long and 1.70m wide joined together, creating bridge's width of 3.5m. The beams are made of two layers PVC coated fabrics. The compression elements and the bridge deck is formed fiber-reinforced pultuded panels and FRP profiles. The tension elements, which are located at the bottom of each beam, are steel cable. Finally, for the supports transverse steel beams fixed at the end of the compression elements for the anchoring are used. The final weight of the standard span of 12m is just 5tons and its load capacity up to 30tons.

According to the referred data, the bridge can be erected easily in about eight hours with a team of eight workers. During the erection, firstly, the deck panels are aligned and the longitudinal steel bars are introduced through the joint area. Then, the inflate process takes place in an inverted position on the ground and due to the fact that the two beams are individualized inflate, it can be performed in a parallel process.

The advantages offered by the AIR-Bridge are[13]:

1. The inflatable technology, as a completely innovative for emergency bridges.
2. Ultra-Light structure (5tons- 12m)
3. Assembly time in few hours.
4. Logistics and transportation volume of about 12m^3. This volume allows to create a stock of dozens of bridges and to storage them in a limited space.

Despite of the promising features of the concept this type of HBC air-beams have not reached the market yet, and are limited to academic and research circles far from the industrial production sector.

In this point of view several question are raised. All air-pressure structure collapses instantly if pressure lost or fabric compromised. So, is it an inflatable structure suitable for an emergency? How much it will cost an innovative solution like that considering the fabrication process based on customized integral solutions with really expensive raw materials? Another important point of view is the machinery (portable air cylinders) that is needed for the erection. Finally, is it feasible to provide the maintenance that all the inflatable structures need under an emergency situation? Although they claim that certain gasses can be captured into these beams for long periods of time without losing pressure. Is this really feasible?

1.3 Research Objectives

By studying previews and existing cases, we sought to identify and expand on lessons learned, address which actions did and did not work well given the circumstances of the incident, and incorporate lessons into the emergency response plan for bridges.

Through the above examples, it become clear that in an "ideal" emergency situation, the combination of the requirements of speed, simplicity, flexibility and economy is essential. Therefore, the initiation of a solution is started through the new proposal design of an emergency bridge.

Unlike other temporary bridging systems that typically require large transport and deployment vehicles and are limited to a fixed span and load capacity, the proposal solution can be deployed rapidly while remaining adaptable to different gaps, providing a cost-efficient solution.

According to these, the four main objectives, which will define the proposal de-

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[13] Challenges in the development of the new air-bridge are the complete functional separation of tension and compression elements in the supporting HBC air-beams, the use of ultra resistant textile or polymer materials in the membrane hull and also as an alternative to cables for the tension element, the increasing high load bearing capacity comparable to conventional steel structures, the use of new compression elements in the HBC air-beams, allowing their foldability after de-inflation, ensuring the suppression of buckling in the compression element by a better elastic embedding on the air-hull, improving the resulting extraordinary light-weight and the adaptivity feature allowing a fast and simple erection and dismantling, small storage volume and easy transport. These unique properties make the air-bridge developed in the project extremely attractive for surface transport vehicles and goods, as well as for many other applications in civil engineering.

Figure 1.9 | AIR-Bridge

innovative technology
lightweight

=

speed

[unsafe, standard span, expansive]

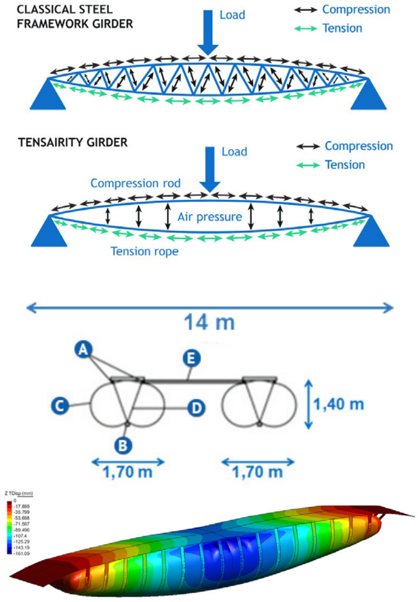

Figure 1.9 | AIR-Bridge [1.17]
AIR-Bridge is based on tensairity, which is a revolutionary technology for the construction of light-weight large-spam space coverings and fast-deploy bridges. Pneumatic technology that complies with the most demanding resistance, efficiency and safety requirements.

sign, are:
1. Speed in Erection (time)
2. Simplicity in Transportation and Erection (effort)
3. Flexibility in Design (span variety)
4. Economy

As it shows in Figure 1.10[14], the research objectives are divided into two categories. The first one refers to the main design objectives (speed, simplicity, flexibility and economy) and the second one to the standard product objectives (quality and sustainability).

1. Speed: The main goal is to achieve an instant bridge structure, which is intended to provide rapid solutions in an emergency situation. The speed has to deal with the erection- how rapid it can be installed. Quick erection means functional bridging can be in place just few hours after delivery.

2. Simplicity: The design focuses on research and development of an emergency bridge, easy to transport (high mobility), erect and relocate, without the need of special equipment or knowledge.

3. Flexibility: The bridge must be adaptable in design with multiple span configurations providing flexibility of use in a wide range of emergency applications.

Moreover the term flexibility refers to the ability of the design to reverse con-

---

[14] There are some specific characteristics, which are commonly used to access the performance of a successful product development effort [1]:
1. Development time (duration): How quick did the team complete the product development effort? (Speed)
2. Product quality: How good is the product resulting from the development effort? (Quality)
3. Does it satisfied costumers needs? (Flexibility)
4. Product cost: What is the manufacturing cost of the product? (Economy)

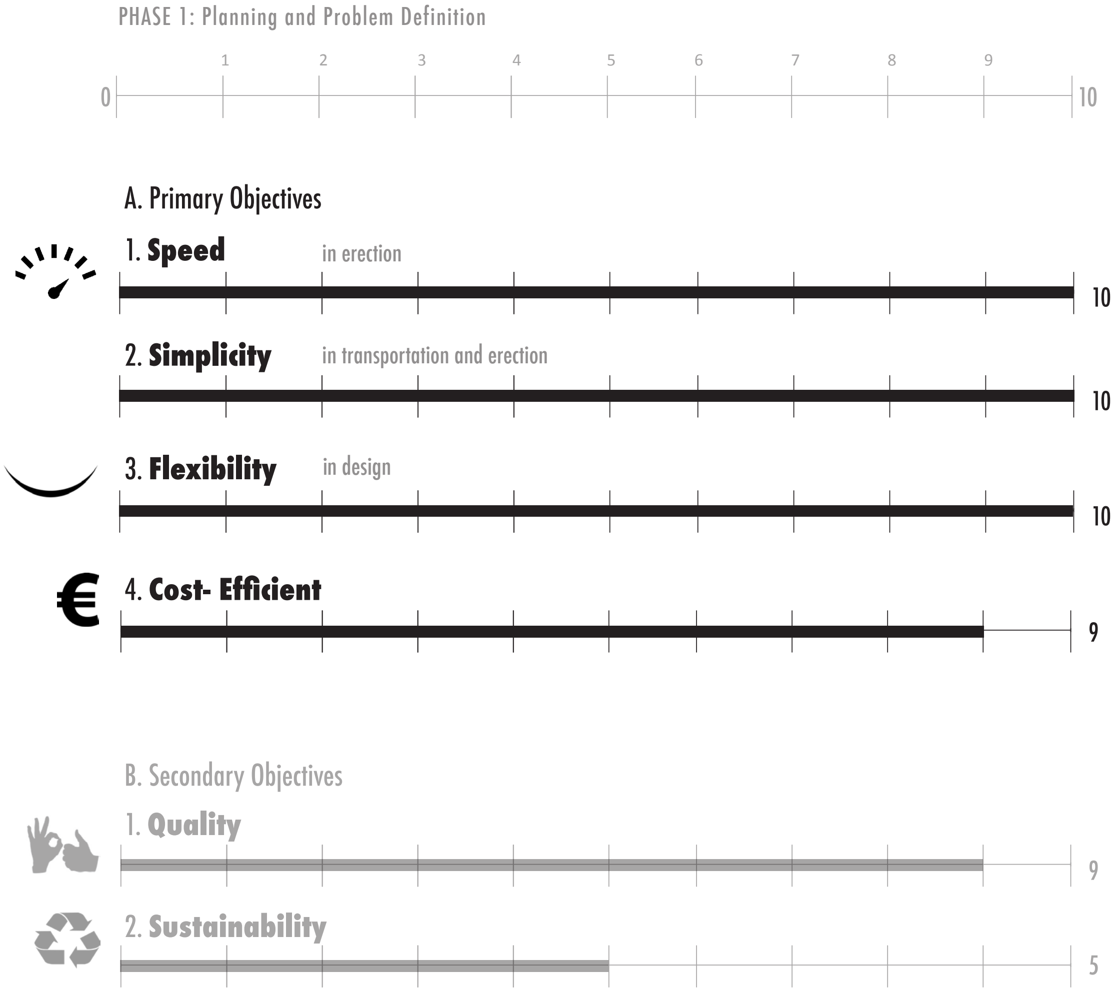

Figure 1.10 | The Primary and Secondary Research Objectives

struction process allowing disassemble, transportation and relocation to another site.

4. Cost: The cost is related to material, fabrication, construction, transportation, installation and maintenance expenses. The concept is based on a cost-efficient solution, economically acceptable by specific purchasers like Red Cross or national governments.

Therefore, attention must be taken to the technological trinity of material selection, shape and manufacturing techniques and how these can be combined efficiently with the former objectives creating a cost-efficient solution.

5. Quality: Although the bridge is applied for temporary purposes, it must follow the requirements of safety, reliability and precision providing structural strength, stiffness and stability. Durability is a key criterion, as the structures are often used for periods far exceeding their initial planned duration, they are reusable but mainly they are exposed in extreme conditions such as rain, fire or earthquakes.

6. Sustainability: Although in emergency cases sustainability is not a priority, the manufacture and transportation are intended to be as sustainable as possible, while its relocation feature makes it reusable/ sustainable.

1.4 Research Question

How to provide services to the transportation community, through the design of a temporary bridge, which is fast, simple, flexible and cost effectively constructed, transported, installed and uninstalled?

How operational considerations and material developments can lead to an evolutionary and sophisticated concept for emergency purposes?"

1.5 Requirements

The requirements for the proposal bridge system involve a hybrid of the design requirements of the three types of military missions in combination with some worldwide regulations. Between the data that are shown in Figure 1.11, of particular interest are the span and the vehicle loads. Other data, like impact and safety factor as well as storage capacity will be analyzed later.

The design of a bridge involves clarification of the overall conditions from topography through the type of use up to technical parameters. These conditions are the requirements of the proposal bridge and they are divided into three categories [Figure 1.12]:

a. Firstly, the functional requirements, which are related to the capacity and the usage of the bridge,

b. Then the geometrical requirements, which are more technical aspects and

c. Finally, the design ones according to the research objectives[15].

Due to this special character of the bridge and its international nature, the reference requirements are taken from a combination of the civil but also military bridge regulations. Therefore, the AASHTO Code (American Association of State Highway and Transportation Officials)[16] [1.25], the EN (European Standards for Bridges)[17] [1.24]

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[15] In order to specify bridge's requirements the following five Ws questions must be answered:
who, when, why, where and how. [1.1]
Think of the capacity as the answers to the questions who—simply, who is involved? (people, victims or relief workers and emergency vehicles)
Think of the time as answers to the questions when— simply, when is it needed? (instantly for emergency purposes and simultaneously temporary)
Think of the purpose as answers to the questions why—simply, why is this needed? (for emergency help)
Think of the location place as answers to questions starting with the word where—simply, where is the being installed? (international character)
Think of form as answers to the questions what—simply, in what form should be fit in and what assumptions should be made about its context?
Finally, think of the material and geometry as answers to the questions how—simply, how should the former requirements be transformed to the proposal solution?

[16] AASHTO (American Association of State Highway and Transportation, 17th edition 2002) is a standards setting body, which publishes specifications, test protocols and guidelines, which are used in highway design and construction throughout the United States.
The AASHTO was first published in 1931, following a period of development that commenced in 1921, and has been widely used for the design of highway bridges in the Unites States of America and elsewhere. [1.25]

[17] Eurocodes are a harmonized set of European structural design standards (EN) for the design of buildings and civil engineering works and construction products, produced by the Comité Européen de Normalisation (CEN).
For the proposal design the suitable Eurocodes are: EN 1990 (Basics of structural design), EN 1991-2 (Traffic loads on bridges) and finally, EN1999-2 (which is related with aluminum as the selected material)
Eurocodes cover in a comprehensive manner all principal construction materials (concrete, steel, timber, masonry and aluminum), all major fields of structural engineering (basis of structural design, loading, fire, geotechnics, earthquake, etc) and a wide range of types of structures and products (buildings, bridges, towers and masts, silos, etc). [1.24]
There are 10 Eurocodes, each published in a number of separate parts:
Eurocode 0: Basis of structural design
Eurocode 1: Actions on structures
Eurocode 2: Design of concrete structures
Eurocode 3: Design of steel structures
Eurocode 4: Design of composite steel and concrete structures
Eurocode 5: Design of timber structures
Eurocode 6: Design of masonry structures
Eurocode 7: Geotechnical design
Eurocode 8: Design of structures for earthquake resistance
Eurocode 9: Design of aluminum structures
The Eurocodes are designated EN 1990 to EN 1999 respectively.
Each of these 10 Eurocodes are in a number of separate Parts - there are 58 parts in total.
Eurocode 0 (EN 1990): Basis of structural design
EN 1990 establishes Principles and Requirements for the safety, serviceability and durability of structures, describes the basis for their design and verification and gives guidelines for related aspects of structural reliability.
Eurocode 1 (EN 1991): Actions on structures
EN 1991 provides comprehensive information on all actions that should normally be considered in the design of buildings and other civil engineering works. It is divided into four parts. The first part being divided into subparts that cover densities, self-weight and imposed loads (EN 1991-2); actions due to fire; snow; wind; thermal actions; loads during execution and accidental actions. The remaining three parts cover traffic loads on bridges, actions by cranes and machinery and actions in silos and tanks.
EN 1990 is intended to be used in conjunction with EN 1990 to EN 1999.

Bridge Application	Assault	Tactical and Line of Communication
Span (m)	8-18m	up to 32m
Vehicle Load (tons)	40T	50-60T
Impact Factor	1.15, for speed<15km/h	1.4, for speed up to 25km/h
Safety Factor	1.5 (ultimate strength)	1.5 (ultimate strenght)
	1.33 (yield strength)	1.33 (yield strength)
	1.5 (buckling strength)	1.5 (buckling strength)
Storage/ Transportation Package	12.20x2.70x2.60m and <17000kg	based on C130 transportation

Figure 1.11 | Design Requirements of the three types of Bridge Missions [1.4]

and the military code TDTC " Trilateral Design Test Code", which is based on the MLC (Military Load Classification)[18] [1.26] of vehicles, are used as design standard.

The first two are regulations for permanent civil applications while the third one is an argument of different countries all over the world and it refers to temporary, deployable bridge for military purpose, which is closed to some of the proposal objectives.

1.5.1 Functional Requirements

The function of the bridge is the first and the most basic requirement. It is specified how the bridge will be used and it will strongly influence its form (geometrical requirements), the material it is made from as well as its construction, transportation and erection processes.

1.1 Purpose

The purpose of a bridge is the answer to the question: *what it is aiming for?* It embeds the bridge in its technical, social, cultural, and historical context.

The proposal bridge will serve emergency situations either as replacement of the existing bridge or as an alternative emergency route.

Furthermore, this solution is temporary (for short term) instantly installed after the disaster until the former bridge is repaired or replaced or until the emergency need is recovered.

1.2 Capacity- Loading Class

For most bridges the main purpose is reasonably obvious and simply captured. Footbridges, highway bridges, and railway bridges carry pedestrians, road traffic, and trains, nothing very complicated about that, except that different structural solutions may be required for spanning over rivers, railways, roads, or deep valleys. [1.1]

As an instant connection for emergency calls, the bridge is going to carry people and vehicles (mainly "emergency vehicles"[19]). Consequently it is classified in combined categories of road and pedestrian bridges.

1.3 Traffic Loads and Restrictions

In general, only one vehicle is allowed to be on the bridge at any time with weight less than 40tons[20]. Moreover, there is a speed limitation of 25km/h.

1.4 Safety

Although a temporary solution, safety is also a priority.

The bridge and its structural members should be designed executed and maintained

---

[18] The military code " Trilateral Design Test Code" (TDTC) is a code agreed between Germany, US, USA and query for the "Quadripartite ABCA (American, British, Canadian, Australian and New Zealand Armies' Program)" from 1974. It is fully focused on deployable bridges, which are identified as standard bridges within the U.S military field. As a worldwide agreement, it has an international acceptance. [1.26]

[19] Emergency Vehicle is a vehicle designed and authorized to be used under emergency conditions to transport personnel and equipment, and to support the suppression of fires and mitigation of other hazardous situations. An emergency vehicle may exceed otherwise applicable vehicle weight and size.
A maximum gross vehicle weights of 86,000 lbs (40tonnes).
Approximately dimensions: Width- 2600mm, Height-4100mm and Length- max 20000mm.

[20] Bridge capacity falls in the categories of LM1, HS20-44 (approximately 40tons) and MLC40 (40tons) vehicles according to EN 1991-2, AASHTO and TDTC respectively. In a further development step, the weight limitation can be increased, increasing the load capacity of the bridge.

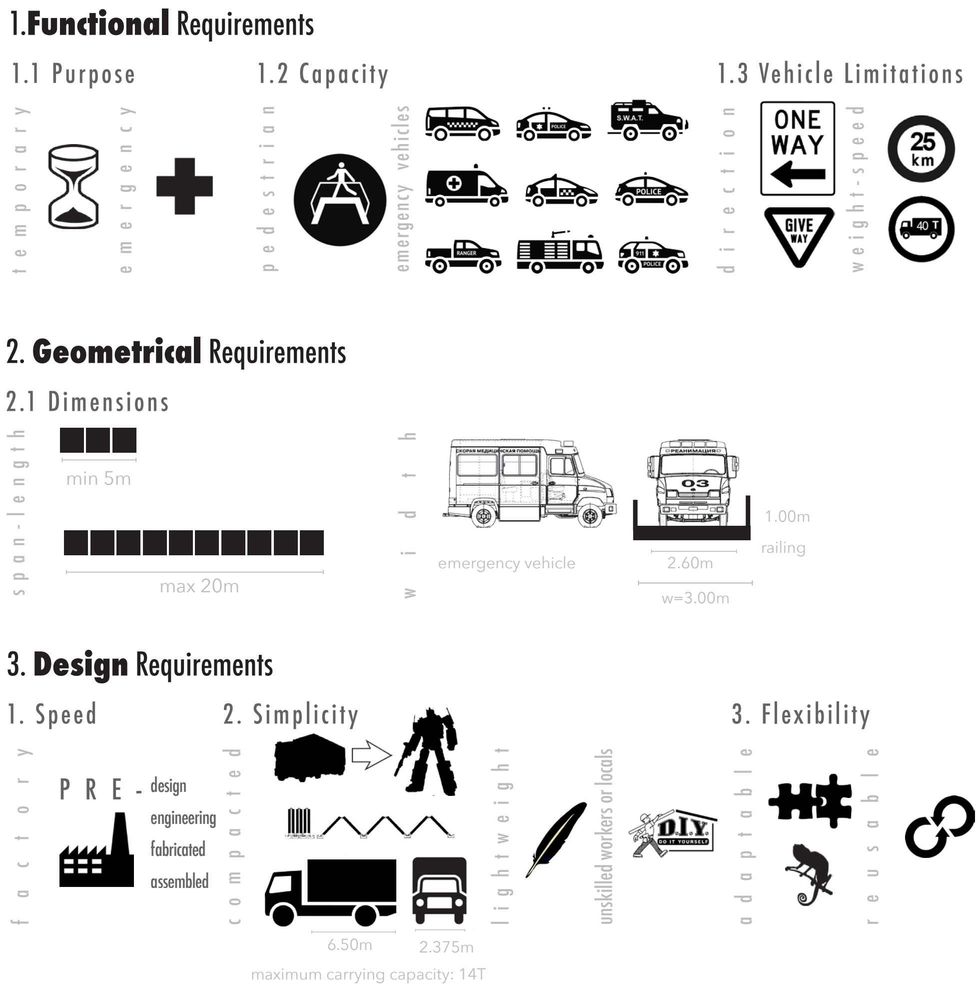


Figure 1.12 | Visualization of all requirements

in such a way that they meet the Eurocode, AASHTO and TDTC principal fundamental requirements, which includes the structural strength, stiffness, stability and durability- robustness. The structure must be able to stand firm during its intended life whatever happens (natural or man-made hazard) providing the appropriate degree of reliability and sustaining all actions and influences likely to occur during execution and use. High winds, heavy rain, earthquakes, tidal waves and even terrorist attacks have to be resisted.

1.5 Maintenance

Finally, low maintenance and replacement capacity are also important in the proposal design.

1.5.2 Geometrical requirements

Some of the geometrical requirements are following the Eurocodes, AASHTO and TDTC codes while some other the defined by the design objectives.

2.1. Dimensions

2.1.1 Length

As a bridge has a prototype character, it has to be able to bridge different spans creating various solutions. This span varies from 5 to 20meters. Although, the span of 20meters is set as a maximum limitation for the current project, in a further development scenario, this could be increased offering even more flexibility as it will be explained in conclusion chapter.

2.1.2 Width

In a conventional bridge design the width determined by the relevant Bridge Code. However, in an international, emergency solution the requirement is to ensure the safe movement on it.

It is single-line but both directional, allowing only one vehicle to be on it and although it is both foot and road bridge, there is no distinct separation.

The carriageway width (w), which is the running surface of the road will be slightly bigger than the notional width, which theoretically is the distance between the white marking lines markings (w_n). According to the Eurocode, the width of a notional line for a single-lane (n=1) bridge is 3.00m. In proposal solution, this minimum value of 3.00m is used and therefore the carriageway line is equal to notional line.

2.1.3 Railing

Various demands are made on a bridge railing. The minimum height of a conventional pedestrian railing has to be 1000mm (41inches) above the top of the sidewalk and must be able to withstand horizontal loads up to 0.8KN/m^2 [1.3].

2.2 Components

The components are prefabricated, standardized and interchange able enabled mass production. The aim is the use of as less component variety as possible (eliminating the catalogue of components) facilitating in this way the fabrication and installation processes. The connecting components demands simple and reliable jointing techniques.

2.3 Access point

The access level has to be as close as possible to the existing shore level in order to avoid big extra elements.

1.5.3 Design requirements

The bridge project also involves the planning of fundamental design requirements. According to the problem statement and the research objectives, the four main requirements, which will define our proposal design, are: speed, simplicity, flexibility and economy. These four characteristics are generating certain design requirements.

3.1 Compacted form

Where transportation and mobility are central concerns, constructions have to be transported (portable solution) and stored as compact as possible. The structure is designed with maximum packing efficiency so that large structures may be collapsed and transported by a truck (Truck limitations: dimensions- width and length and maximum carrying capacity) without the need of special transportation vehicles.

3.2 Pre-completed

As time factor (speed) is crucial in an emergency case, the bridge has to be pre-design, pre-engineering and pre-fabricated. The elements will be pre-constructed and pre-assembled in the factory (off-site manufacturing process) and then transported and installed in a limited time.

3.3 Lightweight

The structure has to be as lightweight as possible for easy transportation and installation and therefore the selection of materials is very important.

3.4 Low labor force

The mechanisms for erection, dismantling and relocation must be easy understandable by unskilled workers or locals by the use of common tools.

3.5 Flexibility

The idea is based on an adaptable design with a broad range of span options through on-demand applications. It will be suitable for various configurations by adding or subtracting elements, providing variable gap-crossing options. The modular nature of the product uses interchangeable standard components, which can be tailored covering different circumstances.

3.6 Demountable

As a temporary structure the bridge has to be able to re-install elsewhere by adjusting it in its new place. It must be constructed and dismantled repeatedly and therefore all the on-site connections are limited to temporary ones.

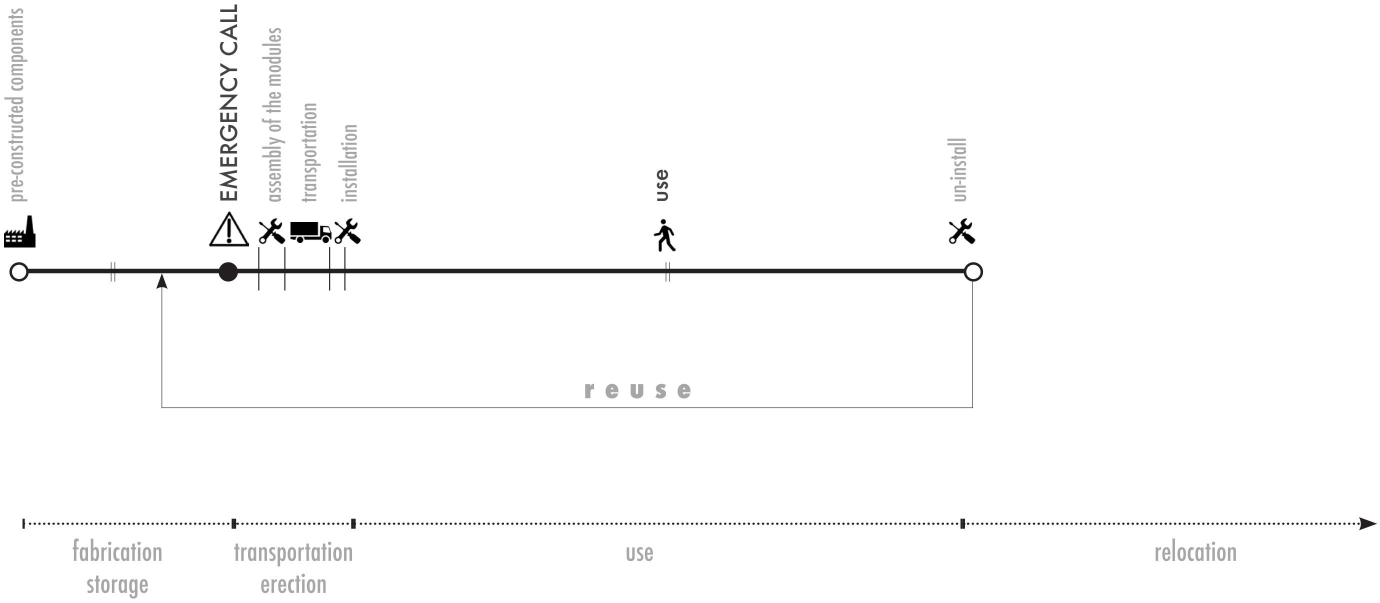


Figure 1.13 | The storyline of the Construction Process

1.6 Storyline

The storyline of the general concept can be described as following [Figure 1.13]: All the elements of the bridge are pre-fabricated. These pre-constructed components will be storage and when there is an emergency call, a requested number of modules according to each circumstance, will be assembled, packed and be ready to transport by a truck. Locals, volunteers and unskilled workers realize the erection in few hours. After the final installation, the temporary bridge is ready for use crossing rivers, canals or any other obstacles just after the disaster, until a new permanent bridge is constructed or the old one is repaired or until there is not any more the need of the connection. Finally, the temporary bridge is uninstalled and packed to reuse in the next emergency call.

2.

Concept Development

Concept Development Phase is based on research. Its activities include the selection and deeply analysis of the working principles- design strategies- of the product and the architectural approaches that best meet the project's requirements based on a design through research approach. These decisions are afterwards transformed into technical solutions.

In DeMoLi bridge concept, the applied strategies are: Deployability, Modularity and Lightness. For designation of Lightness, material selection is carried out through CES EduPack software and finally, the selected materials are analyzed.

2.1 Design Strategies

The Concept Development Phase gives fundamental descriptions regarding three key features, which are combined to optimally meet the specified requirements. These are *Deployability, Modularity and Lightness* that form the *DeMoLi Bridge* [Figure 2.1].

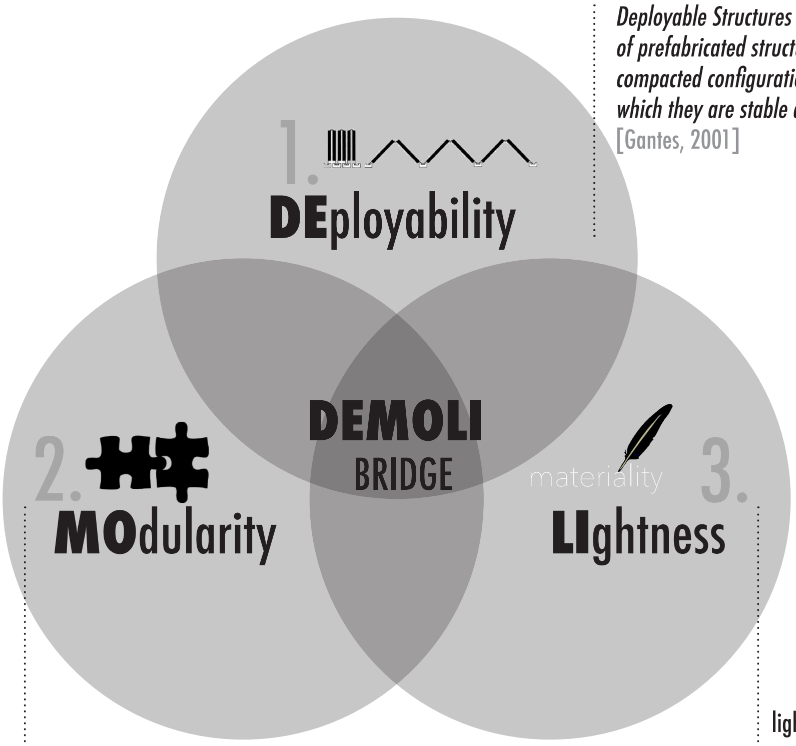
Deployable + Modular + Lightness = DeMoLi Bridge

There is no doubt that the above terms can work together efficiently covering the objectives of the emergency bridge. The terms Modularity and Deployability are inextricably linked and in combination with the selection of a proper lightweight material can offer the promising solution.

In order to achieve the desired requirement of a compacted form during transportation, the structure follows the rules of Deployability. It is based on movable elements, which can be really compacted for easy transportation and simultaneously durable and large, when they are deployed for use. The bridge is both transportable and transformable. Transportable because of its ability to relocated and transformable due to the fact that it can change shape. In general, transformability is needed to make its transportability easier. Deployability concerns not only the pre-manufacture of the elements but also the pre-assembly of the entire structure in a factory and the deployment on site.

Secondly, the term *Modularity* is described and analyzed, since the bridge consists of a standard-base, prefabricated, repeatable modules, which can create different length configurations due to its adding and abstracting ability. Thanks to modularity, the flexibility is an easy step and the structure is able to bridge every gap. The interchangeable components can be kept in storage and adapted to the specific site immediately after the disaster.

DEployablity + **MO**dularity + **LI**ghtness = **DeMoLi Bridge**



Deployable Structures is a generic name for a broad category of prefabricated structures that can be transformed from a close compacted configuration to a predetermined, expanded form, in which they are stable and can carry loads.
[Gantes, 2001]

"Modularisation = decomposition of a product into building blocks (modules) with specified interfaces."
[Ulrich and Eppinger, 2004]

lightweight
strong
stiff
durable
cost-efficient

Figure 2.1 | The three De-Mo-Li (sh) Strategies

The last term is the *Lightness* and it is related to the materiality of the structure. The bridge has to be apparently stable, durable and long lasting, both in term of materiality and construction like every conventional bridge. However, in an emergency situation there are two other features, which are also important. These are the weight of the structure in combination with its cost. The proposal bridge has to be made of lightweight materials facilitating transportation and installation and simultaneously, providing a cost-efficient solution.

2.2 Deployabilty

2.2.1 Definition

"*Deployable Structures is a generic name for a broad category of prefabricated structures that can be transformed from a close compacted configuration to a predetermined, expanded form, in which they are stable and can carry loads*" [2.5].
Normally, when we apply pressure to an object, it may respond by bending, breaking, squashing or resisting inertly; however, many other responses are also possible. Specific controlled behaviors such as expansion, dilation, fold, and shape change in general can be designed into an object adding to it, the term of deployability.
Deployable structures are capable to vary their shape from a compact, packaged configuration to an expanded, large, deployed, operational state without any damage by an autonomous and reliable way [2.11]. The transformation from the former to the latter state is called deployment and the reverse action is called retraction [Figure 2.2].
The flow of a deployable structure could be described as following:
Initially, the structure is transported in a compacted bundle configuration at the

site. Then, the force that is applied to the object is transformed in controlled motion, which deploys it. Once the form of the structure has been changed, the movable elements of the system are locked. Then, the structure “freezes” in place to its deployment configuration signaling the transition from a mechanism to a load bearing.

Typically, deployable structures are used for easy storage and transportation and they are deployed into their operation configuration when required. Therefore, they can be characterized as convertible structures because they are changing both their form and mode for operation [2.12] but also as a special case within the boarder class of adaptive ones due to their inherent transformability. Furthermore, they are typically understood as temporary transportable structures that can be reused and relocated relatively ease and quick, reducing working time at the site.

They consist of elements linked together in the factory, satisfying a pre-assembly geometry and packaged in a compact configuration. Thus, the erection is operated very simple by articulating the various components of the structure, resulting in fast installation and deployment process to complete large-span structures. [2.5]

By definition, a structural system is a combination of resistant bodies intended to sustain loads (loadbearing structures). In general no internal mobility or relevant motion among the members are allowed. On the other hand, a mechanism in machine theory is commonly identified as a set of moving or working parts used essentially as a means of transmitting motions or controlling movement of one part relative to another. It is often assembled from gears, cam and linkages, or more special components like springs, ratchets, brake and clutches [2.13].

Deployable objects fall in a family of unconventional structures that are capable of large shape changes due to the ability of the members to move when a force is applied on them. They are a hybrid between structural and mechanism systems- structure and mechanism at the same time, creating a *motion structure*, where the links of the mechanism, which normally transfer motion, are identical with the structural elements, which provide support. [2.12].

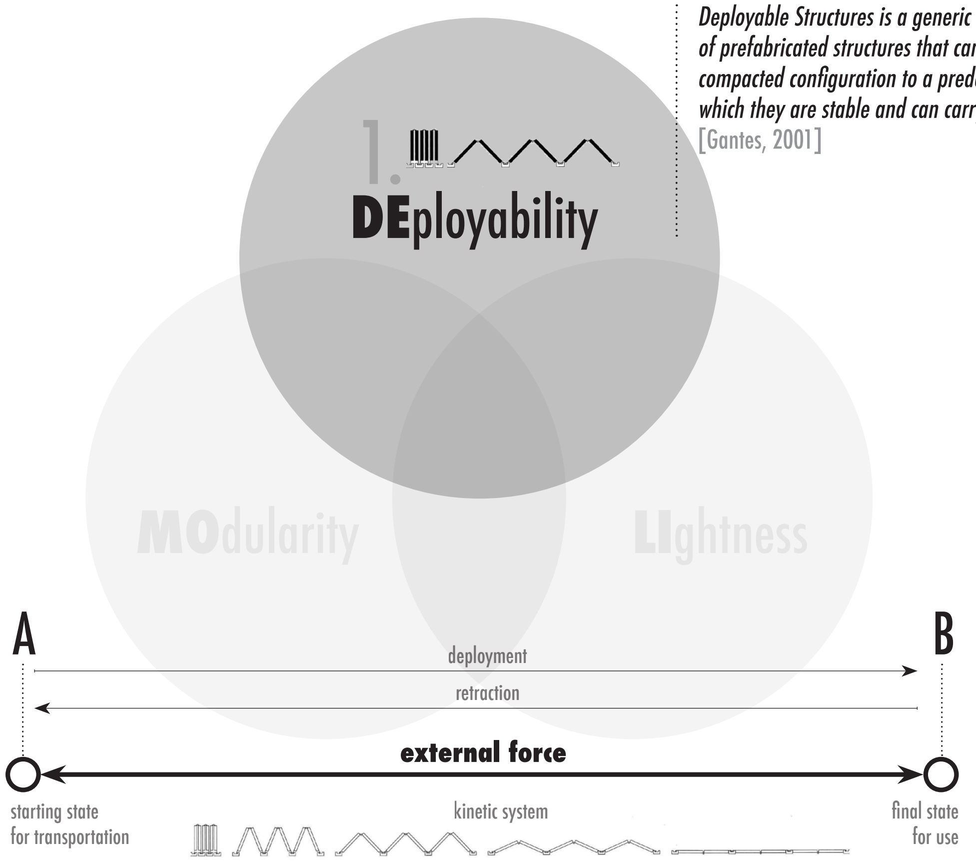
There are close similarities as well as distinct differences between a motion structure and a conventional mechanism. Firstly, the primary function of a motion structure is to have shape alteration essential to practical requirements, rather than transmitting or controlling motions. Secondly, a motion structure is usually composed of far more parts than a conventional mechanism. Thirdly, motion structures generally use fewer but more robust types of joints because of the environments in which they typically operate. Moreover, when synthesizing motion structures, the positions and operations of the parts during the motion are far more important than other physical properties such as velocity and acceleration, as the cycle time of motion structure is generally in a matter of minutes or hours rather than seconds or less for conventional mechanisms [2.13]. Finally, normally mechanisms are not seen as integral objects and the emphasis during the design is on producing trajectories to achieve a particular function.

Applications for deployable- collapsible structures vary including masts, slabs, grids and space frames such as domes and shelters for both earth-based and space applications. They may also be found in many emergency applications like emergency shelters and facilities, through re-locatable and semi-permanent structures. [2.4]

2.2.2 Advantages

Architects and engineers demonstrated a growing interest in studying and experimenting with motion structures since they offer important advantages over other systems [2.7]. There are numerous practical reasons to make a deployable object and most of them fall into the DeMoLi design requirements:

1. *Speed*: The erection process of deployable structures is both rapid and easy,



Deployable Structures is a generic name for a broad category of prefabricated structures that can be transformed from a close compacted configuration to a predetermined, expanded form, in which they are stable and can carry loads. [2.5]
[Gantes, 2001]

Figure 2.2 | The flow of deployable structures

Figure 2.2 | The flow of deployable structures
A: Starting, compacted, packaged state- static system
A-B: Due to the external force, a movement results and the static system becomes kinetic one. Kinematic refers exclusively to a temporal process of motion.
B: Final, expanded, loadbearing, operational state- static system

since it results from simply deployment its compact form made of pre-assemble elements, in couple of hours or minutes.
2. *Trans(form-port)ability*: The main reason for making collapsible products is clear: mobility. Due to its compact shape (small volume) in folded form the pack for storage and transportation become really easy.
3. *Re-usability*: Dismantle for reuse is simple, since shrink and re-deployment are easy, fast and inexpensive. There is a contemporary perception that portable buildings are low-quality tools, cheap and disposable. However, temporary in sitting does not necessarily mean temporary in existence, but it characterizes its ability to move in order to reuse or recycle.
5. *Cost*: Finally, the cost is competitive compared to other alternatives. Deployability implies an extra cost over an assembly structure due to more sophisticated, expensive, movable connections, locking mechanisms, and complex design, which cost time, money and effort in both design and construction phases. This extra cost is balanced by the structure's greater potential.

2.3 Modularity

2.3.1 Definition

"*Modularisation = the decomposition of a product into building blocks (modules) with specified interfaces*." [1]
We live in a dynamic economic and commercial word surrounded by objects of remarkable complexity, sophistication and power [2.2]. Leading companies are meeting these challenges with a focus on modularity. Modularity is a concept that has proved useful in a large number of fields that deal with complex systems. These fields range from brain science and psychology, to robotic, psychology, neurosci-

ence, artificial intelligent and industrial engineering.

In everyday language, the word modularity is used almost as a synonym for the concept of “composed of parts”. In broadest terms, modularization is an approach for organizing complex products efficiently, by decomposing the tasks into simpler portions able to managed independently and yet operates together as a whole. [2.9] Hence, modularity refers to the ability to assemble a larger system on-orbit from a number of individual intelligent units, based on the idea of interdependence within and independence across modules [2.2].

Modular systems are built from highly independent (“loosely coupled”) units/components, which are called *modules* [2.6]. These modules have features that enable them to be coupled together to form the complex form. The interactions between them are few and well defined by specific design rules. Through standardization of interfaces, modularization permits components to be produced separately and used interchangeably without compromising system integrity. [2.8] A module never works alone but as an aggregation of multitude of instances. It is never unique but part of a larger self-similar structure that tackles multiple requirements, such as program, structure and constraints originating from material properties, geometry and fabrication. Thus the whole emerges out of the interaction of a series of individual objects.

2.3.2 Standard Components

A modular architecture allows the use of standard components[1]. Component standardization is the use of the same component or module in multiple products or in the same product for multiple times and is closely linked to product variety. Such standardization allows the firm to manufacture the chunk in higher volumes. [1] Under most circumstances a standard component is less expensive than a component designed and built for one product and its use can reduce also the complexity and lead-time of product development. Finally, standard components exhibit higher performance (for a given cost) than unique designs.

2.3.3 Modularity in Architecture

Current architecture industry, also the bridge construction industry, is based on all-in-one communications management unit (integral design). Such systems lack flexibility but they are associated with efficiency and controlled, easier and faster designing. If a firm adopts integral product architecture, it is required to follow a unit of a completely specific ‘‘ideal’’ input to produce a final good. On the other hand, modular approach provides a flexible, cost-effective and adaptable design. In this case, components are designed to interact with one another through standardized and codified interfaces. [2.14]

Modular constructions appeared in the history of architecture many centuries ago. They fulfill the necessity of subdivide structural elements in order to achieve easier, faster and cheaper fabrication, transportation and assembly of build entities. [2.1]

Vitruv introduces the notion of module (modulus) while analyzing the Doric rhythm of Pantheon. He defines the module as the smallest possible unit in which each element of the temple can be analyzed in. Modular constructions were further developed to perfection during the industrial era. Modular constructions were standardized, enabling them to be manufactured in millions. The homogeneous identical module, easily reproduced by the existing technology, still revolutionizes architectural construction today [2.1].

Over the past century, these processes have developed a stigma of “cheapness” and “poor quality.” However, through modern technology, that image has changed.

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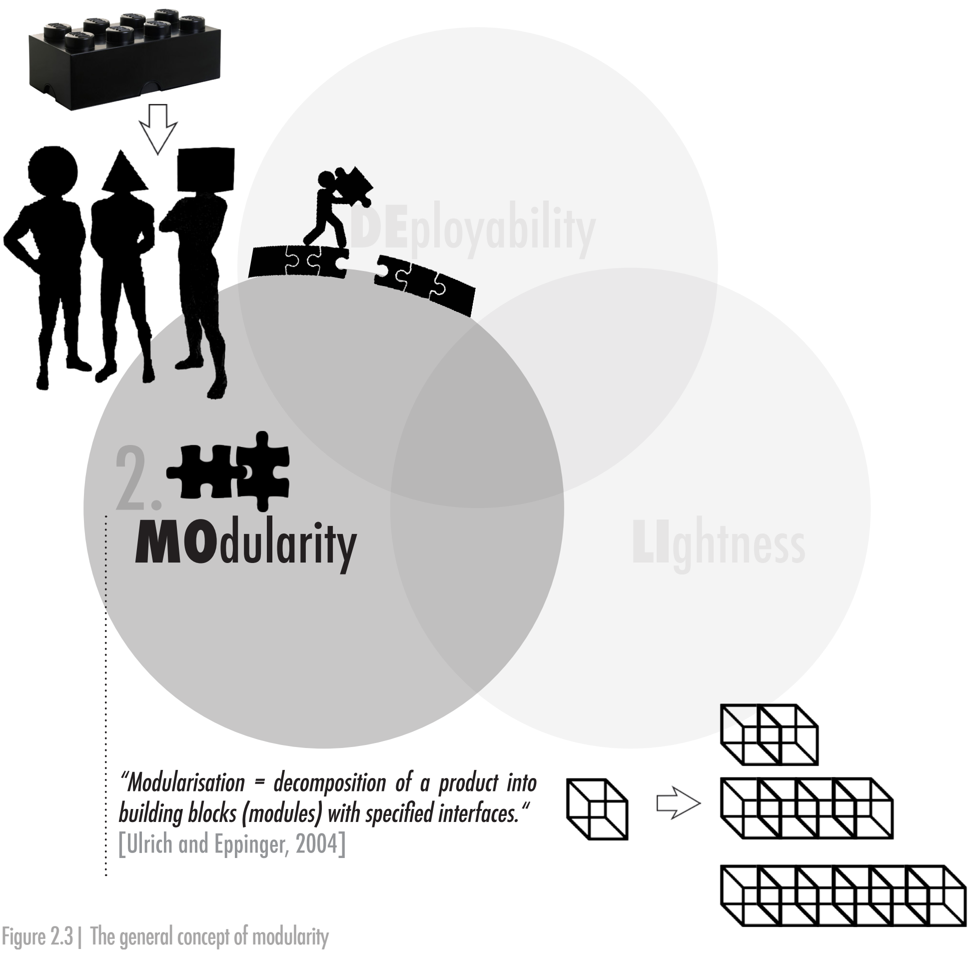
1. Lego- Blocks are modular, standard components, toy manufactured. They are colorful interlocking plastic bricks, which can be assembled and connected in many ways due to their standardized interfaces allowing constructions by combinations. Anything constructed can then be taken apart again, and the pieces used to make other objects.



"Modularisation = decomposition of a product into building blocks (modules) with specified interfaces."
[Ulrich and Eppinger, 2004]

Figure 2.3 | The general concept of modularity

Now, it's a key component of the drive to improve construction industry productivity.

Historically, the main use of modular construction was in portable or temporary buildings, but this prefabricated construction technology using volumetric units is now used in a wide range of building types, from schools, hospitals, offices, and supermarkets to high-rise residential buildings. Designs using load-bearing modules date from the early 1990s.

Modular construction provides a new way of building based on factory-made (off-site) units, under controlled plant conditions, that are transported and installed on site to create the complete structures. These applications highlight the key benefits of rapid and high-quality construction, and economy of scale in manufacture.

2.3.4 Advantages and Disadvantages

Modularization and off-site construction obtain advantages in design, production and installation, focused on certain market sectors, where there is a demand for speed and safe construction, flexibility, simplicity and economy in manufacture.

1. *Speed*: As it is shown in Figure 2.3, time is significantly the bid-win for modular off-site structures, because of its ability to achieve a rapid, reliable construction program by reduced exposure to risks, such as adverse weather conditions, increasing productivity in factory production and limiting requirement for on-site labor. In modular and other off-site construction methods, slow unproductive site activities are replaced by more efficient and faster factory processes reducing up to 50% the construction time.

2. *Simplicity- Flexibility*: Modularity is a simple but powerful concept, which, it raises the possibility of complex structures using very few different elements. As the

module is multiple by its self, the final product can have different configurations [Figure 2.5].
Modularity= Simplify Complexity + Amplify Variety [2.3]
3. *Re-usability- Transportability:* Modular structures are both demountable and re-usable due to their portability. Portability implies that it can be broken down into pieces (or modules) small enough to be carried to the work place by a human operator and quickly assembled. Each module would have to be carefully designed to be lightweight and durable. Such a weight restriction creates an unusual demand to use special lightweight materials.
In addition components can be replaced, changed and improved over time without redoing the whole.
4. *Cost*: The primary economic benefit is the speed during the construction process. Shorter build times lead to reduction site of management costs. Initial element cost may be more expensive but savings from off-site benefits should be considered.
5. *Quality*: Higher quality is achieved by the factory-based construction process and pre-delivery checks. The independent components can be produced and tested separately before they are integrated into a modular product [2.6].
6. *Sustainability*: The off-site manufacturing process in modular construction offers many sustainable benefits that arise from the more efficient manufacturing and construction processes, the improved in-service performance of the completed building and the potential reuse at the end of the building's life.
Moreover, used and wasted materials are reduced because off-site manufacturing processes lead to more efficient bulk ordering of materials in the correct sizes for the particular project, and to less site damage.
Finally, there are greater opportunities for recycling in factory production.
7. *Mass customization*: Initially, the focus on customer needs leads to customized products, which means that companies have to manage a greater variety of products. Secondly, competition enforces companies to strive for efficiency in the business chain: to reduce costs, increase quality and reduce response time. Modularization is often mentioned as a means for handling these seemingly conflicting demands - and frequently in connection with the manufacturing concept of mass customization. The idea is that a broad variety of products can be produced by combining a number of modules. In this way modularity balances standardization and rationalization with customization and flexibility [Figure 2.4] [2.8]. This is despite the fact that for many years it was a common thought that companies had to choose a strategy as either mass producing- standardization at the expense of customization and efficiency. Modularization, through mass customization, can ideally lead to satisfy particular customers requirements while still maintaining the efficiency and low development cost of mass production.
However, there are serious obstacles to the increased use of modular solutions, which are associated with the difficulty of the design and construction community to respond to this new ways of working:
1. *Lack of knowledge* among the design community of the solutions that are available and uncertainty of how to integrate modular manufactured systems into an otherwise traditional construction process. Furthermore, there is a tendency of some members of the client professional team to regard the use of off-site solutions as something novel, unknown and therefore inherently risky and best avoided.
2. It turns out that modular systems are much *harder to design* than comparable interconnected systems because at the end all the independent components have to function together as a whole.

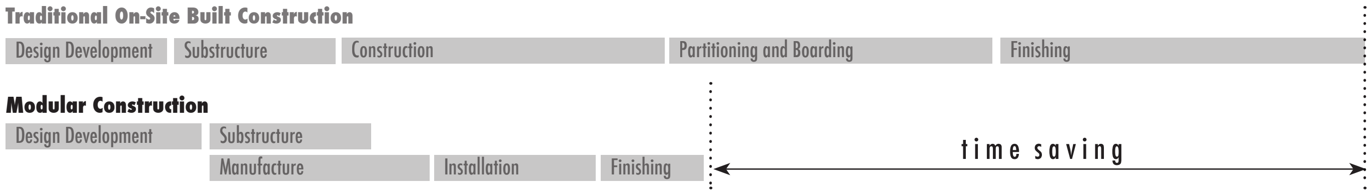


Figure 2.3 | Time Consuming

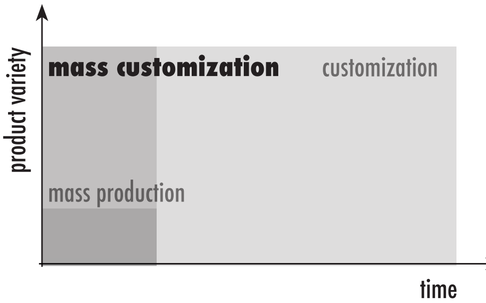


Figure 2.4 | Mass Customization

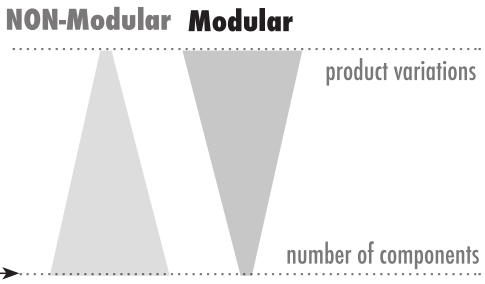


Figure 2.5 | Variety and Number of Components

2.4 Lightness

2.4.1 Definition

Lightness can be read in many different ways and it deals with various subjects. Although all these are interrelated, at this point of view, Lightness refers to the materiality of the structure.

The list of materials from which bridges are made is actually quite short. It includes steel, concrete, timber, stone, metal alloy, such as aluminum alloy and stainless steel, or advanced composites materials like GFRP or CFRP.

In an ideal structural design, the function, form and materiality have to be seamlessly interwoven. The choice of the "right" materials can influence the success of the final structure and therefore it has proved critical to efficient bridge construction, especially when there are extra requirements such as emergency, modularity and deployability. All of the three former characteristics require a material, which it will be *durable* with *high capacity* but also *lightweight* and *cost-efficient*. Consequently, the structure should be made out of materials which are at the same time light for easier transportation, strong enough to stand the stresses and deformations to which the structure is subjected, durable under extreme weather conditions and cheap in order to meet the emergency requirements. The last term related to the economy can be described regarding the material as: "Doing more (strength of the structure), by paying less (material cost)".

In bridge constructions, the aim should always be the use of as less material as possible. Using less material means dispensing with the superfluous and allowing the principles of lightweight construction: *build structures as light as possible and as rigid as necessary* [2.18]. The durability of the bridge's material is also important, especially in an emergency situation, due to the extreme conditions that it will be exposed. Finally, deployable structures are particularly subjected to different form of stresses and strains and therefore the choice of appropriate materials must accordingly be given special consideration.

Generally, there is a constant struggle to achieve durability, high strength and stability on the one hand and lightweight on the other minimizing the energy required to move an element [2.12].

Figure 2.3 | Time Consuming
Comparison between traditional on-site built and modular construction regarding the time consuming.
(50% time saving)

Figure 2.4 | Mass Customization
Mass production is a production of a large number of identical or very similar components to realize the benefits on economies of scale.
Customization is a production of specified components according to individual specifications
Mass Production + Customization = Mass Customization
It has the advantages of both, speed of mass production (fast) and variety of customization (flexibility).

Figure 2.5 | Variety and Number of Components
Modularity decreases the number of parts while increases the number of product variety.

As a result, the main properties of the materials relevant for its use in emergency bridge construction and more specifically in DeMoLi Bridge are the following:
1. *Lightness*, referred to the density of the material,
2. *Strength*, which is translated into the yield strength of the material (elastic limit),
3. *Notch toughness*, which is the Young's Modulus and
4. *Durability of the material*, which is related to its weather resistance under certain conditions such as rain, sun etc.

3.4.2 CES EduPack Analysis

In order to define the "right" materials, the educational edition of the Cambridge Engineering Software (CES EduPack 2014) is used, at the beginning as a database with material lists and after the selection as an encyclopedia of properties.
The material selection process in CES EduPack starts with the database of Architecture[2], which includes all the available materials that are used in the field of architecture. In total, there are 127 available architectural materials, which belongs to the following nine categories:
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers

In order to limit the given results, several limits are applied according to the design requirements. These limits are set by filters, related to the geometry of the structure that the material applies to, the mechanical properties- strength and stiffness, the durability of the material and finally the density. The results from each stage are presented with CES EduPack graphs. Specifically, graphs with density (x-axis) vs yield strength (y-axis) are used to visualize all the different stages until the final selection [Figures 2.7-11].
Analytically, the limit filters are formed as following:
Stage 1: The first limitation is related to the building system and the material form that data applies to and the input is superstructure[3] and bulk (for solid objects) respectively. The results, after this filter, are reduced from 127 to 75 because all the materials belong to families of foams, fabric and fibers, elastomers and polymers are rejected.
Stage 2: The second limitation deals with the weight of the structure. Due to the fact that lightness is really important the density is limited to the maximum value of 4000kg/m^3. After that only 54 results stay to the list.
Stage 3: Then, several filters relevant to mechanical properties are set. Defining the stiffness and the strength of the material a range between 20-400GPa and the maximum value of 100MPa are used as limitations for Young's Modulus[4] and Yield Strength[5] respectively. The remaining materials are only 8 materials and belong to the families of Glass, Composites, Metal: Ferrous and Non-Ferrous and Technical Ceramics.
S*tage 4:* The last limitation deals with the durability of the material and more specifically its resistance to water both fresh and salt as well as to weak acids.

---

[2] Database: Architecture
Selection form: MaterialUniverse: All Architecture

[3] Superstructures are all the elements that transfer static and dynamic loads from the structure down to the foundation or the substructure. [CES EduPack]

[4] Young's Modulus is the slope of the initial, linear-elastic part of the stress-strain in tension and compression. [CES EduPack]

[5] Yield Strength is the stress at which is first suffers permanent (inelastic) deformation in tension. [CES EduPack]

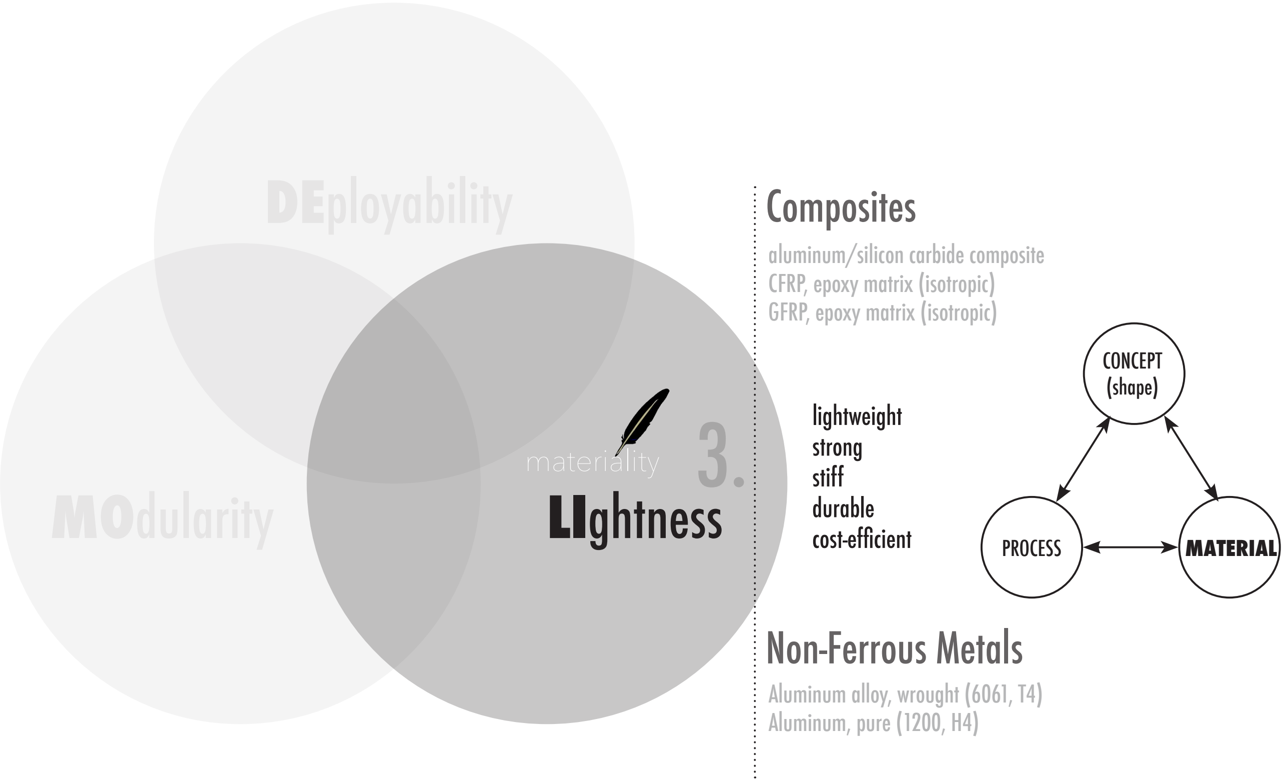


Figure 2.6 | The two families of the remaining materials according to CES analysis and the trinity essence [2.15]

Figure 2.6 | The trinity essence [2.15]
Every single functional object evolves from the process that turns and the selected material into a functional form, which are the inevitable trinity of technology. (material- shape- process)
There is no shape without material and effort.

Water (fresh): Excellent
Water (salt): Excellent and Acceptable
Weak Acid: Excellent
Strong Acid: Excellent and Acceptable

The six remaining materials are shown in Figure 2.11 and they belong to the three families of Composites, Non-Ferrous Metals and Glass.

Composites: CFRP, epoxy matrix (isotropic), GFRP, epoxy matrix (isotropic) and Aluminum/silicon carbide composite,
Non-Ferrous Metals: Aluminum alloy, wrought (6061, T4) and Aluminum, pure (1200, H4),
Glass: Silica Glass (Vycor).

The family of Glass with Silica Glass is rejected for several reasons. Firstly, due to its optical properties (transparency), it is mainly used for facades applications. Furthermore, it is exceptionally hard to be shaped, requiring either very high temperature or special processes by which it is formed after. This makes the construction process expensive and in general inappropriate from bridge solutions.

The other two families of Composites and Non-Ferrous Metals are going to analyzed and tested further in Design Verification Phase through the material comparison.

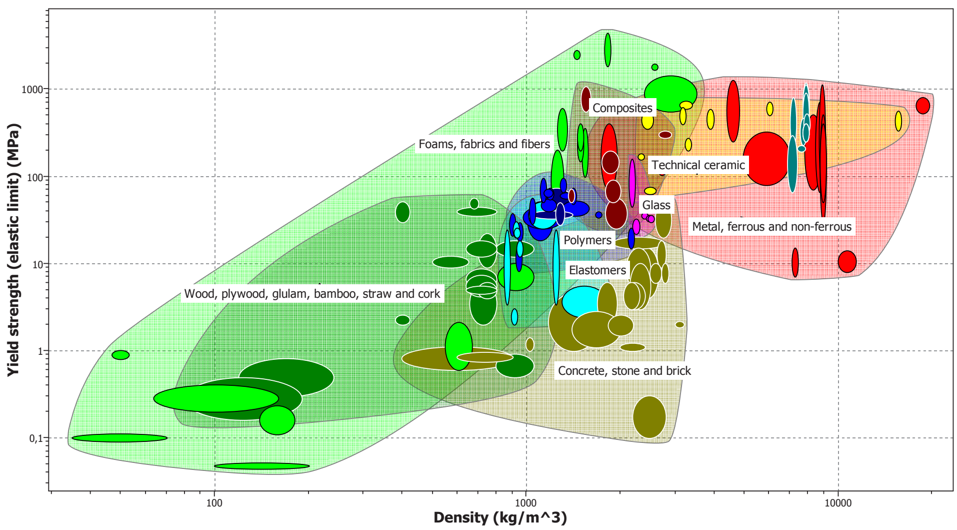
Four graphs relevant to the density, the Young's Modulus, the Yield Strength and finally the density*price are visualized giving a general idea of the compared materials. [Figures 2.12-2.15]. CFRP seems to be to the strongest, stiffest and simultaneously the most lightweight material, however its cost is extremely high. It has a similar Young's Modulus (much higher than other FRP) with aluminum and at the same time a much higher strength and much lower density.

CES analysis (127/127)

Figure 2.7 | Starting point
1. Selection Data
Database: Architecture
Selection form: MaterialUniverse: All Architecture

Results: 127/127
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers

Stage 1: Yield strength (elastic limit) (MPa) vs. Density (kg/m^3)

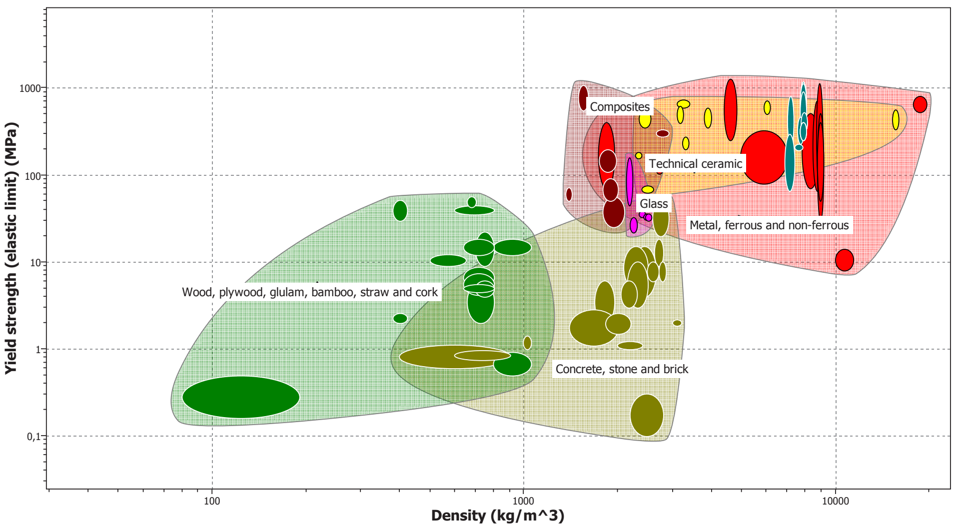


Stage 1: Material Form (75/127)

Figure 2.8 | Stage 1: Bulk, Superstructure
1. Material form that data applies to: bulk
2. Form building system: Superstructure

Results: 75/127
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers

Stage 1: Yield strength (elastic limit) (MPa) vs. Density (kg/m^3)

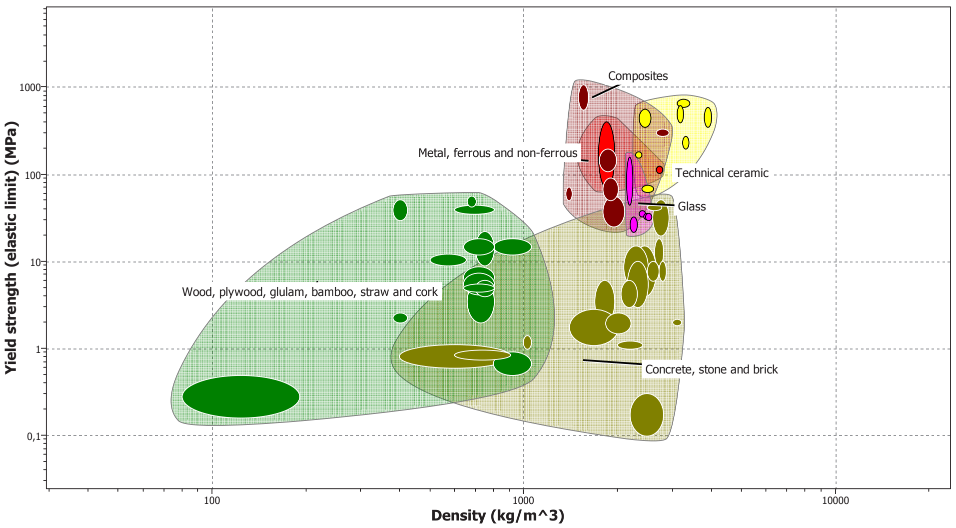


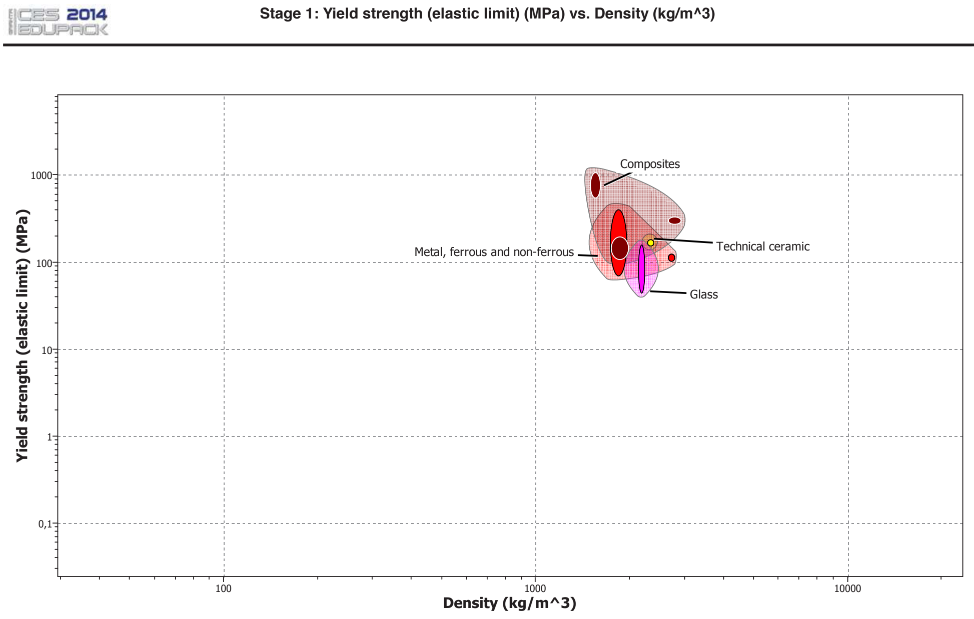
Stage 2: Density (52/127)

Figure 2.9 | Stage 1:Density
General Properties
Density: maximum 4000kg/m^3

Results: 52/127
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers

Stage 1: Yield strength (elastic limit) (MPa) vs. Density (kg/m^3)

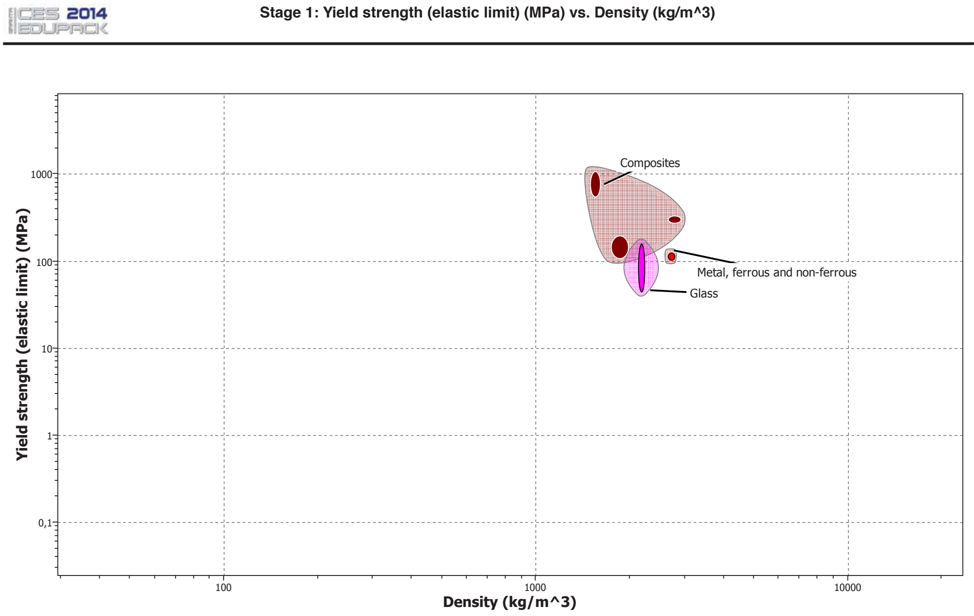




Stage 3: Mechanical Properties (8/127)

Figure 2.10 | Stage 3: Young's Modulus & Yield Strength (elastic limit)
Mechanical Properties:
Young's Modulus: 20-200GPa
Yield Strength: min 100MPa

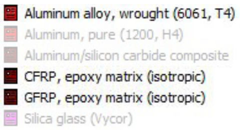
Results 8/127
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers



Stage 4: Durability (6/127)

Figure 2.11 | Stage 4: Water (fresh), Water (salt), Weak Acid
Durability
Water (fresh): Excellent
Water (salt): Acceptable and Excellent
Weak Acid: Excellent

Results 6/127
1. Composites
2. Metal, Ferrous and Non-Ferrous
3. Glass
4. Concrete, Stone and Brick
5. Technical Ceramic
6. Wood, Plywood, Glulam, Bamboo, Straw and Cork
7. Foams, Fabrics and Fibers
8. Polymers
9. Elastomers


▨ Aluminum alloy, wrought (6061, T4)
▨ Aluminum, pure (1200, H4)
▨ Aluminum/silicon carbide composite
▨ CFRP, epoxy matrix (isotropic)
▨ GFRP, epoxy matrix (isotropic)
▨ Silica glass (Vycor)

GFRP is also a lightweight and costly solution, whereas its mechanical properties are much lower in comparison with CFRP. Especially its Young's Modulus is one fifth than CFRP. This is why it is not easy to achieve long spans.
The third composite, aluminum/silicon carbide, is the most economical solution between the three and its mechanical properties are balanced between the two others composites but it is a heavier solution, as its density is higher.
Finally, both Non-Ferrous Metals have almost same properties. Their weight is similar to aluminum/silicon carbide composite and despite the fact that they are cheaper in comparison with all the composites materials its yield strength is similar to GFRP while its Young's Modulus is more or less the same as CFRP.
The following two parts describes the two remaining materials' families.

2.4.3 Non-Ferrous Metals (Aluminum)

Aluminum is a soft but tough construction material. Its strength is similar to steel's (100MPa), while its mass density is approximately 2700kg/m^3 (one third compared with steel).
Aluminum's advantages are related to its good material efficiency, stability, dura-

Figure 2.12 | Graph of
y-axis: Yield Strength (MPa)
VS
x- axis: Density (kg/m^3)
CFRP is the most lightweight and the strongest material.

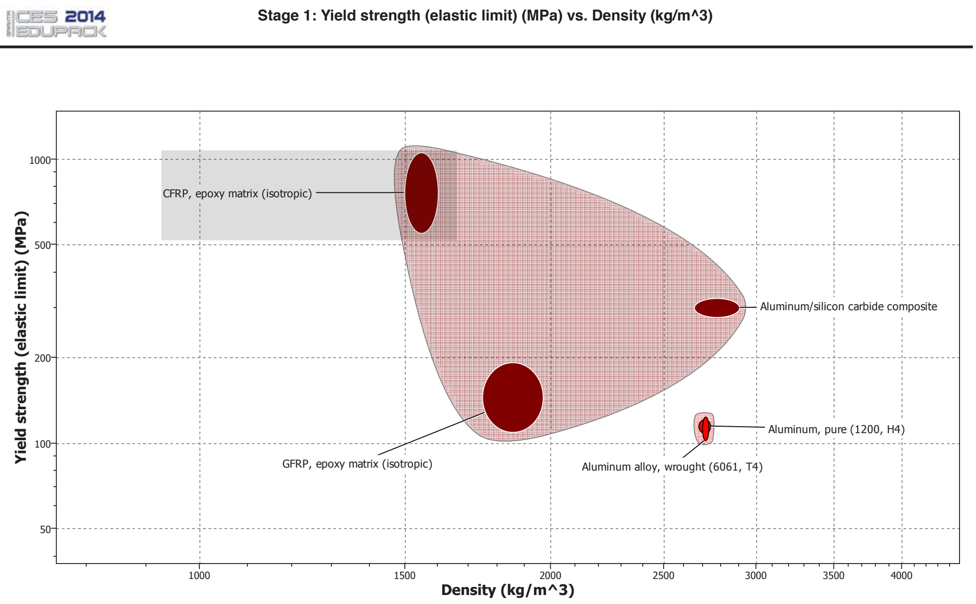
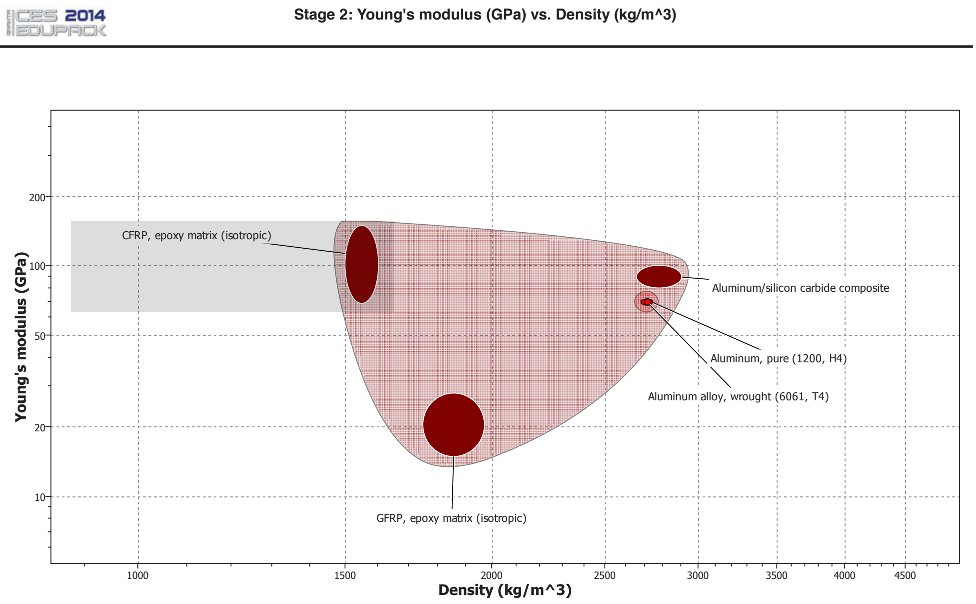


Figure 2.13 | Graph of
y-axis: Young's Modulus (GPa)
VS
x- axis: Density (kg/m^3)
CFRP is also the stiffest material.



bility and low maintenance in combination with high strength to weight ratio. Aluminum has a breaking length three times greater than that of construction steel, an indication of its capacity despite its low weight. It can be worth considering for use in components exposed to high levels of mechanical stresses and structural elements that require a minimal use of material and weight. Prefabricated construction methods make it even more economically solution [2.18].

Furthermore, aluminum is not only corrosion resistant, but unlike other materials it can survive harsh environmental conditions without any extra treatment, like protective coating. This is due the fact that aluminum and aluminum alloys react with oxygen and water vapor in the air to produce a thin, compact oxide film, which protects the underlying metal from further attack [2.19].

Its disadvantages are its low fatigue strength and difficult jointing techniques. Manufacturing aluminum also uses a great deal of energy, which negatively affects its ecological balance.

Regarding bridges for emergency purposes, aluminum alloy can be used instead of conventional concrete or steel materials to satisfy their primary requirements: lightweight for transport facilities, modular feasibility, faster construction and

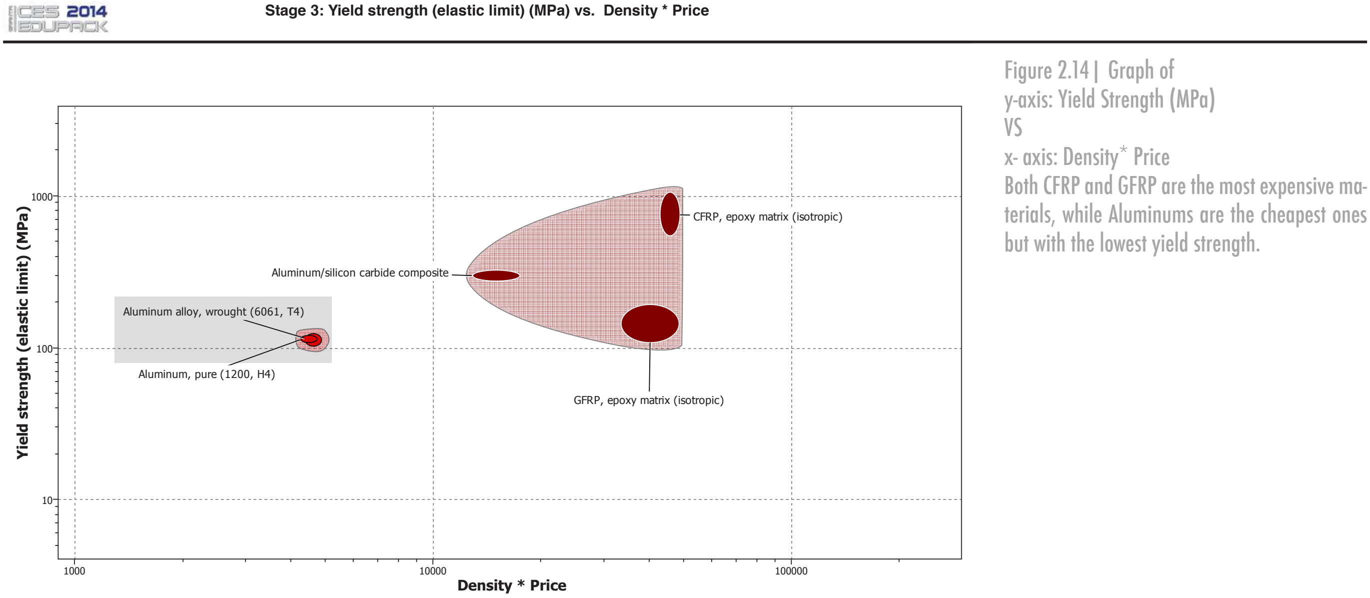


Figure 2.14 | Graph of
y-axis: Yield Strength (MPa)
VS
x- axis: Density* Price
Both CFRP and GFRP are the most expensive materials, while Aluminums are the cheapest ones but with the lowest yield strength.

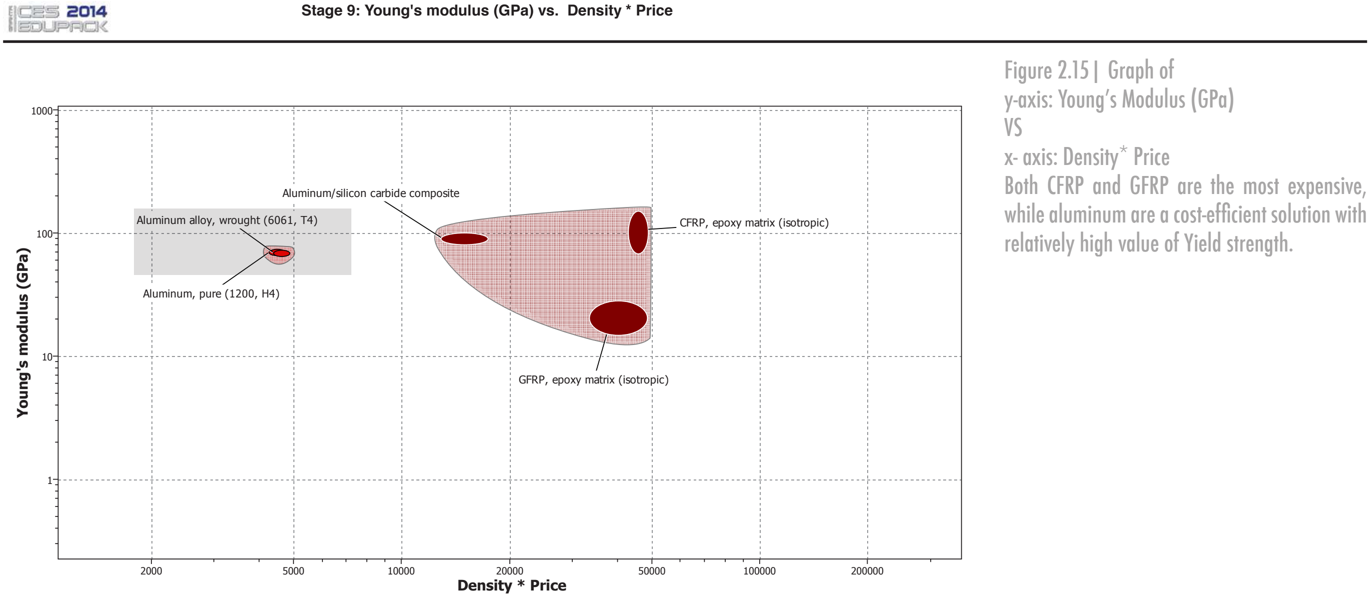


Figure 2.15 | Graph of
y-axis: Young's Modulus (GPa)
VS
x- axis: Density* Price
Both CFRP and GFRP are the most expensive, while aluminum are a cost-efficient solution with relatively high value of Yield strength.

cost-efficiency.

The results from CES analysis show that two of the six materials are aluminums. More specifically, these are aluminum alloy, wrought (6061, T4) and aluminum, pure (1200, H4).

Aluminum, as pure material (1200, H4) purposes to medium strength applications related to chemical and petrochemical, domestic electrical appliances and building components [CES EduPack]. However, in real construction, the structural materials are alloys of aluminum such as the second remaining non-ferrous metal: aluminum alloy, wrought (6061, T4). This is used for trucks, towers, canoes railroad cars, furniture and other structural applications such as bridges, where strength, weldability and corrosion resistance are needed. Therefore, between the two materials with so similar properties aluminum alloy, wrought (6061, T4) is selected for the further analysis.

2.4.4 Composites (FRP)

Composites are one of the great material developments of the 20th century. According to the CES analysis, the three composites according to the input filters are CFRP, epoxy matrix (isotropic), GFRP, epoxy matrix (isotropic) and finally, aluminum/silicon carbide composite.

Aluminum/ silicon carbide is a metal-ceramic composite material reinforced with particles of silicon carbide or aluminum. The reinforcement increases the stiffness, strength and maximum service temperature without seriously increasing the weight. Hence, their attraction is their stiffness-to-weight and strength-to-weight ratios. The most widely used metal matrix composited is DURALCAN range of alloys based on the 6061 grade of aluminum alloy with 10-30% silicon carbide or alumina. Its typical uses are pistons, engine parts, brake discs, drams and calipers, drive shafts, mountain bike frames, precision instruments and sports equipment [CES EduPack]. It has been never used in bridge industry and therefore is rejected for the current list.

The focus here is on Fiber-Reinforced materials, and more specifically, CFRP, epoxy matrix (isotropic) and GFRP, epoxy matrix (isotropic).

Fiber-reinforced polymer (FRP) materials are notably attractive for structural applications mainly in aerospace, marine and automobile industries due to their excellent properties, such as high strength, good corrosion resistance and low self-weight.

FRP bridge technology has moved rapidly from laboratory prototypes to actual demonstration projects in the field to replacement decks, strengthen existing structures and construct new bridges. Among these applications, the construction of bridge decks, pedestrian bridges, and light-traffic vehicular bridges have been increasingly promoted in last years. Heavily loaded vehicular bridges have also been constructed out of FRP more recently [2.16].

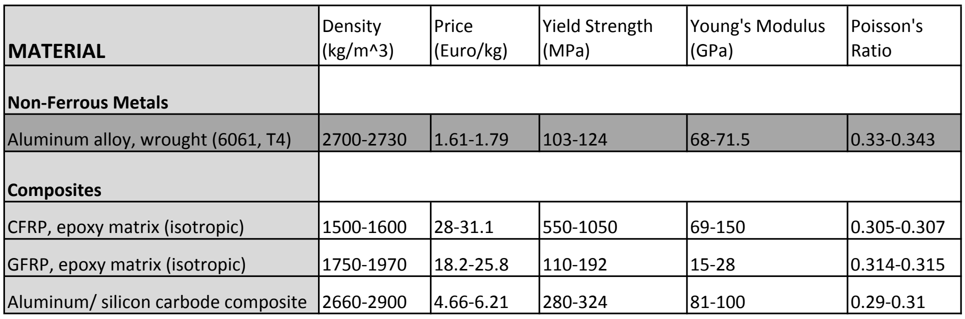
The structural behavior of FRP materials is based on the fact that the fibers carry the mechanical loads while the matrix material transmits loads to the fibers and provides ductility and toughness as well as protecting the fibers from damage caused by handling and the environment.

Analytically, some benefits of the material that are relevant to proposal design are [2.18]:

1. FRP is suitable for complex shapes without a lot of limitations due to the different existing fabrication technologies. New shapes, manufacturing methods, and hybridization with other materials may lead to a more optimal design.
2. Because of its prefabricated nature, it has the ability to speed construction and improvement in quality due to the environmentally controlled factory.
3. It is extremely lightweight, with density from 1500-2000kg/m^3. A lightweight FRP structure can easily transported, assembled and installed on site, in contrast to steel or concrete. As a result time and effort are reduced.
4. Due to its corrosion resistance ability, it lasts longer (it has long service life), in comparison with other materials, while requiring minimal maintenance and the same structure can be used again and again. For example, steel reinforcement and structural steel members are known to be susceptible to corrosion, while concrete could also crack because of sulfate attack, freeze thaw and other detrimental processes. FRP bridges are designed with a 120 years design life and will not corrode.

However, there are certain disadvantages associated with using FRP at the present time, which must be taken into account during the design process [2.17]:

1. The initial cost is probably the largest barrier to widespread use of these materials and it is very important in the proposal design.
2. Some types of FRP, for instance GFRP, have low modulus of elasticity when compared to other materials such as steel or aluminum, which leads to large deflections over the structure. This has a direct affect on the stiffness of it. In order to meet serviceability requirements for deflection, FRP systems are inevitably over



MATERIAL	Density (kg/m^3)	Price (Euro/kg)	Yield Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio
Non-Ferrous Metals					
Aluminum alloy, wrought (6061, T4)	2700-2730	1.61-1.79	103-124	68-71.5	0.33-0.343
Composites					
CFRP, epoxy matrix (isotropic)	1500-1600	28-31.1	550-1050	69-150	0.305-0.307
GFRP, epoxy matrix (isotropic)	1750-1970	18.2-25.8	110-192	15-28	0.314-0.315
Aluminum/ silicon carbode composite	2660-2900	4.66-6.21	280-324	81-100	0.29-0.31

Figure 2.16 | General and Mechanical Properties of the selected materials according to CES EduPack encyclopedia

designed from a strength perspective.
3. The joint and connections must be design carefully.
4. Similarly, uncertainty over material properties gives rise to conservatism and subsequently higher cost. Until manufacturing methods become adopted that assure consistency in material properties that are verifiable with standard testing methods, specification writers will necessarily need to write a tight specification to insure the finished product will be safe and reliable. Moreover, most bridge designers are not experts in composite materials and prefer to stay with well-understood materials rather than venture into the world of new materials and fiber architecture.
4. Finally, they are low fire (they are flammable) and UV-radiation resistance and they usually need an extra coating for protection.

In conclusion, regarding an emergency bridge, where weight is critical for the transportation and erection, and simultaneously durability, strength and stiffness but also the cost parameter become important, the material selection is crucial. To minimize weight, we must maximize material efficiency and hence specific properties.
All the materials have many properties like density, strength, stiffness, durability, cost etc. The choice of the right combination of properties can be quite difficult. An easy way is the use of a performance index, as a way to calculate the best solution. This is presented in the Design Verification Phase through Finite Element Analysis, which defines the selection of the proper materials by comparing the former properties of the three selected materials: aluminum alloy, wrought (6061, T4), CFRP, epoxy matrix (isotropic) and GFRP, epoxy matrix (isotropic).
At this point of view a simple comparison between aluminum and the two composites is made with the help of *material efficiency* (me) formula [2.15]. This characteristic depends on two basic material properties: density (p) and Young's Modulus or Elastic Modulus (E), which expresses the ration between stress and the resulting elastic deformation.
For solid beams, sheet, shells and sandwich elements in only tension and compression (truss) [2.15] [Figure 2.16]:
$me= E/p$
$me_{aluminum}= 70/2.7= 25.9$
$me_{CFRP}= 70/1.5= 46.7$
$me_{GFRP}= 20/1,75= 11.42$
$me_{CFRP} > me_{aluminum} > me_{CFRP}$

CFRP presents the best results but affordable production of the desirable structure is really difficult. Aluminum, offers an attractive solution, combined with the available manufacturing technologies, which are both mature and cheap. Finally, GFRP disappoints.

3.

Concept Design

The Concept Design Phase includes the development of the conceptual product. It involves the intellectual process of developing a research idea into a realistic and appropriate research design.
The conceptual design of a bridge is a step, which the designers must to visualize and imagine the bridge in order to determine its fundamental function and performance before any structural analysis and detailing design are preceded. In DeMoLi solution, this includes consideration of several factors, such as the selection of bridge and deployable system throughout analysis and comparison of existing systems, as well as the description of the selected ones and their application in DeMoLi Bridge.
Consequently, the focus of this phase is two-fold: Firstly, it evaluates the feasibility assessments of the alternatives and secondly, it clearly defines and approves the scope of the project, synthesizing a preliminary design which includes explanation of the system and all the required activities .

3.1 Bridge Form

3.1.1 Type of Bridge

Defining the bridge’s geometry, it is helpful to start by thinking of it, from three different perspectives—purpose, material, and form [3.8]. Both purpose and materiality were discussed during Planning and Problem Definition and Concept Development Phases. The third one, which is the choice of it structural form, is one of the most critical decisions that a bridge builder must make and it is going to analyze further in this third Phase, Concept Design.

The ‘grammar’, of how bridges are constructed, is based on combinations of four sub-structural types: Beams, Arches, Trusses, and Suspensions (BATS) [3.8].

B| *Beam or Girder Bridges* are monolithic and heavy structures, which are usually made of heavy materials like concrete and metals and they rely primary on bending actions. They are the oldest and the most basic bridge form.

A| *Arch Bridges* are symbols of stability, solidity and constancy. The arch is the main structural element, shaped and supported in such a way that intermediate transverse loads are transmitted to the supports primarily by axial compressive forces in the arch rib combined with some bending [3.4]. Firm foundations in arch bridges are especially critical. Once erected, arch bridges will stay in place for a very long time as long as the foundations don’t move.

T| *Truss Bridges* are simple structures, which are composed of equal-sized members, following the rules of modularity, offering simplicity in design and fabrication. They are strong and lightweight, based on triangulated assembly elements. Although, its principles are similar to beams bridges, they are easier to be constructed and transported in comparison with beam bridges due to the short size of the its elements.

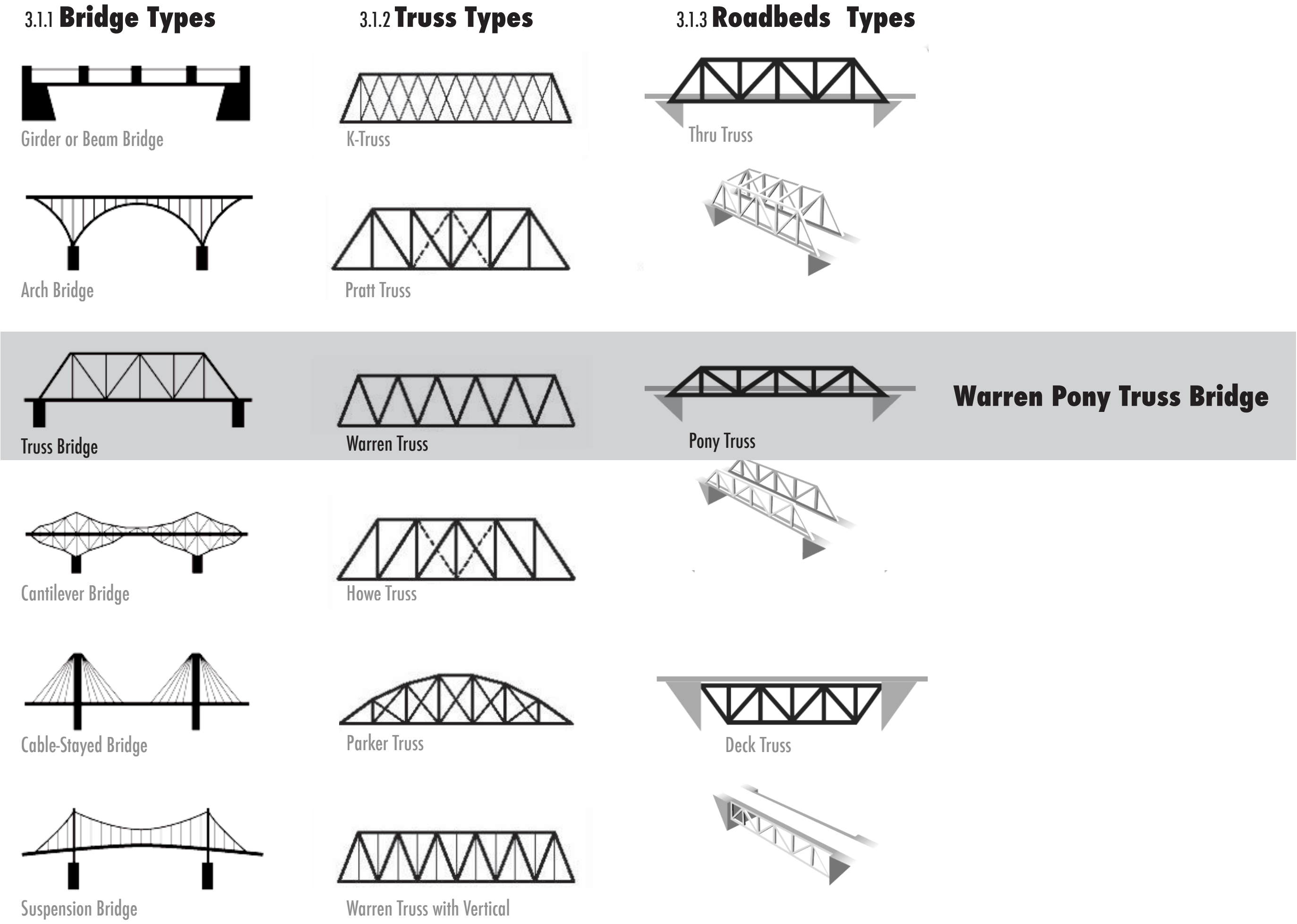


Figure 3.1 | Form selection throuh cescription of bridge;s geometry

S| Finally, the type of *Suspension Bridges* includes cable elements such as support cables, hangers or stayed cables, on which the superstructure is hung from pylons or masts. The elements are usually prefabricated, however the erection time is increased due to the fact that contains thousands of wires with many variations. They are often characterized as landmark structures because they can impress due to their light and daring with long spans.

The type of bridge is determined by factors such as design loads, surrounding geographical features, soil and foundations, passing line and width, the length of the bridge, aesthetics, the requirement for clearance below the bridge, transportation of the construction materials, erection procedures, construction cost and period, etc. [3.5] In DeMoLi case, the most important factor is its emergency character and therefore according to the above features the relevant ones are the design loads (capacity), the soil and the foundations, the general dimensions (width and length) and finally all the restrictions related to the transportation and erection process.
According to the definitions of BATS bridges and the design requirements the type of Truss Bridge fits better to the proposal design. All the others are rejected as they are investing either in stability by using heavy structures or in lightness and impression with element's variety and time-consuming erection processes.
Trusses, on the other hand, are clever, highly interconnected structures, showing the way that complex systems grow out of interacting simpler ones. They can be vulnerable and resilient at the same time. The vulnerability or resilience of a truss 'emerges' from the way that the parts of the truss are connected [3.8].
In general, an engineering truss is essentially a type of frame designed to trans-

mit loads from the structure to the supports. In this way, the permanent loads (mass), and variable loads (traffic, wind) are transmitted safely to the piers and abutments, which in turn transfer the loads to the ground.

Truss Bridges are structures built up by jointing together elements to form an open framework based on triangles, as the simplest shape that is rigid and stable. Due to the triangular form of the truss and the different elements that connected each other, the truss bridges are physical team worker fitting to the term of modularity [3.8]. A simple truss is constructed starting with a basic triangular element and connecting two members to form additional ones. [Figure 3.2]

The members that define the triangulated assembly, are straight, either rods or plates, that are connected at both ends, forming the upper and lower chord, and the web diagonal [Figure 3.2]. Their connections are known as nodes or joints and they are hinges or pins that are illustrated like small circles, as it is also shown in Figure 3.2, because they are able to rotate freely about each other. Therefore, there are no restraints against free rotation and so no internal bending moments [3.8].

When loads are imposed on structures built on this principle, the entire cross section of the elements is loaded only under axial forces, either tension or compression and each of the elements or member of the truss is either being simply pulled or pushed along their entire lengths. Consequently, truss structures are very efficient and the strength of a truss relies essentially on the axial load-carrying capacity of the members. As there is no bending, there is no need for a massive beam any more, creating a more lightweight structure.

Although essentially differs from beam, they bear some points of similarity, with the chord members, regarding as equivalent to the upper and lower flanges of a beam and with the web members forming an open system that replaces the beam's solid web [3.4]. Thus, they dispense with unnecessary material, making a lightweight structure by using efficient use of material. Furthermore, they are an economical alternative to earlier designed beam bridges, because they give more strength than a simple beam bridge due to their great ration of strength to weight. Therefore, they can support in an efficient way heavy loads [1.3]. Their economy lies also to the standardization of the parts.

There are many advantages of having such a design:

1. First and foremost, a bridge built under this concept is very *strong* due to the use of triangles. The triangles are ridged which contributes to the strength of the structure.
2. Engineers have reported the use of much *less material* in the construction of bridges using the truss design.
3. This type of bridge creates *cost-efficient* solutions, optimizing the use of labor and machinery. Costs of material is also less since the design makes the maximum use of materials. Furthermore, the elements are usually being of equal prefabricated length, based on mass production, saving time and money.
4. The span, which is the distance between the end points, has been found to be greater than with other designs especially with single beam designs.
5. Finally, due to the identical and handy components the transportation, erection and repair are easy steps.

However, there are also some disadvantages:

1. Bridges with this type of structure are old and outdated now. Engineers are looking at ways to add to the structures in order to increase their aesthetic.
2. If not designed in the correct manner, it can cause a lot of wastage in terms of material because there can be members in the design that do not contribute in any way to the overall structure.
3. It can use a lot of space and tends to become a distraction to drivers.
4. It is more complex to construct because they are assembled of many parts.

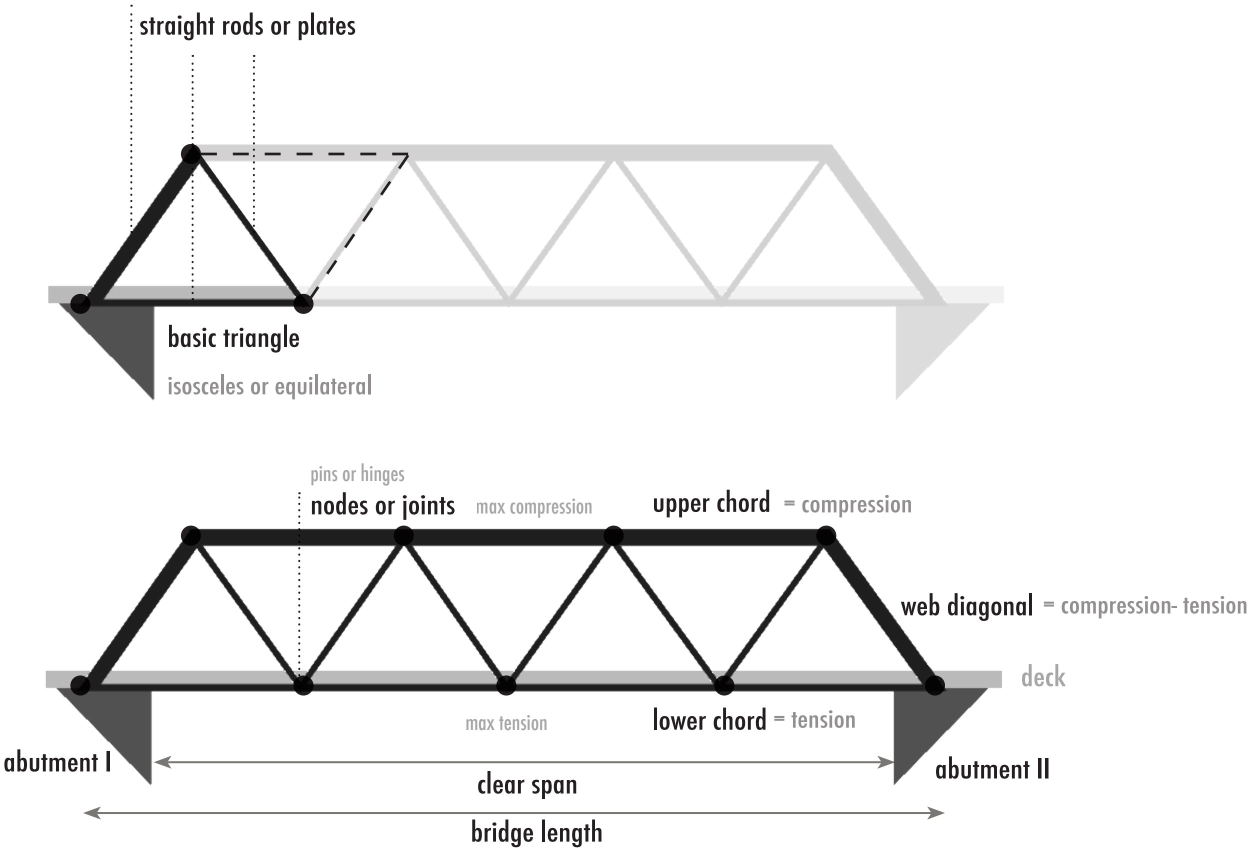


Figure 3.2 | A simplified representation of Warren Pony Truss

3.1.2 Type of Truss

As it is mentioned above, a typical truss is made up of members that are joined together to form triangular sections. The range of possible truss bridge geometries is much greater than shown in Figure 3.1. There is a number of many ways in which members can be arranged to form the truss, and over the years these arrangements have been assigned different names to simplify their identification. Truss types include the Lattice truss, the McDonald truss, the Allan truss, the Pratt truss, the Whipple truss, the K truss, the Warren truss and many more [Figure 3.1]. The best-known truss bridges are the Warren truss, the Pratt truss, and the Howe truss.

The Warren truss is the most common and simplest version, being pretty much one triangle beside the other. The Warren truss without vertical supports is used to bridge smaller spans while the Warren truss with vertical supports is used to bridge larger spans more than 50m.

Pratt truss bridges are made with diagonal supports that slant downward and toward the middle, except for the very end supports.

The Howe truss is the opposite of the Pratt truss. Instead of slanting downward to the middle, the supports slant upward to the middle. Because the supports slant in the opposite direction, they handle compression forces, making it expensive when made in steel and also rarely seen.

During the brainstorming, numerous designs of trusses were considered, which can be combined with deployable methods. Our focus is on trusses made up of identical modules, which are repeated by having the same pattern giving to the system the ability to change the bridge’s length by adding members.

Hence, the traditional Warren bridge, which is a simple design consisting of equilateral triangular trusses is the selected one. It is one of the most traditional designs, simple in terms of construction, and lightweight, which would help fulfill the minimum material goal according to the design requirements.

The Warren Truss Bridge[1] has two parallel chords- the top and bottom chord, which are the horizontal parts that the individual diagonals, which are called web diagonals, attach to [Figure 3.2]. Although, the individual members are very differently stressed, this type of truss is especially suitable for systems made up of identical, equal, standardized individual parts, because all the elements have the same lengths and the detailing points are repeated [3.9]. This configuration combines strength and simplicity with economy and lightness.

3.1.3 Types of truss roadbeds

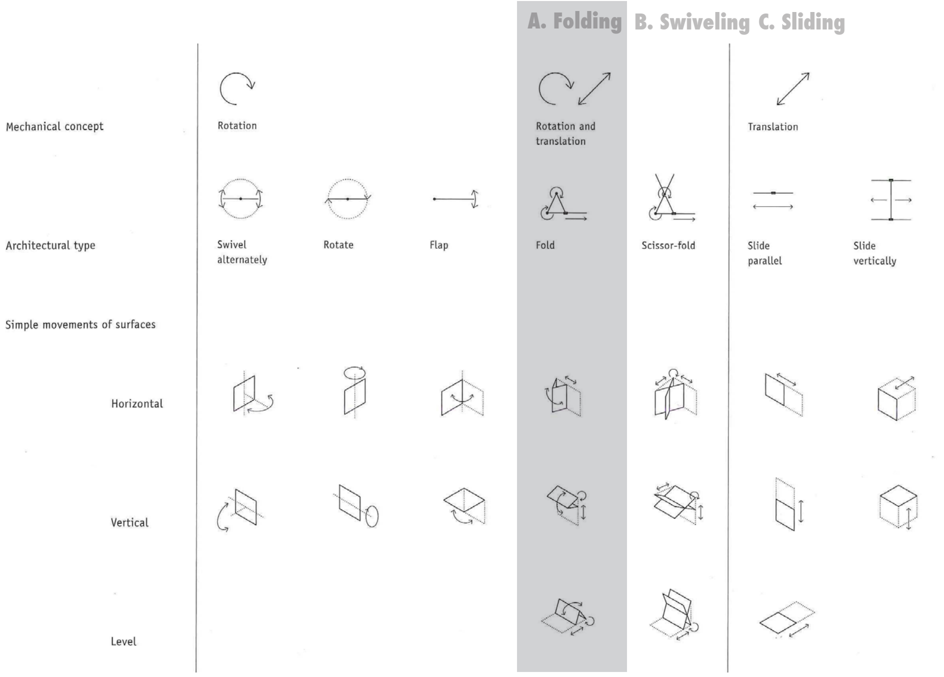
The level of the deck in relation to the bridge can alter dependent upon the design and the specific requirements. There are three types of truss roadbeds. The deck can be above (deck truss) or between (pony and thru truss) the trusses [Figure 3.1].

1. In the *thru truss* bridge the road passes between the truss lines and is carried on the deck and floor system connected to the bottom chords at the panel points, hence the truss is above the walkway. Consequently, the deck travels between and through the truss and all the structural elements are found above the roadbed. The upper chord's stability plays an important role here since it is subjected to compression and there is a risk of lateral deflection. This can prevent either by a proportionate transverse stiffness of the truss girder, or by using struts and diagonals that prevent lateral deflection by exercising an appropriate framing action. [3.8] This type is generally used for spans more than 30m long.
2. A *pony truss* bridge is the same as a thru truss, but it does not have lateral bracing between the top chords. This type is generally used for shorter spans, smaller than 30m long where the height of the truss is also shorter.
3. In a *deck truss* bridge, the road is above the trusses, and the deck system is on the top chords. The deck is attached to and lies above the truss and there are no structural elements above the deck. In this type, it must be ensured that any clearance limits and flood protection regulations applying to the area under the bridge are observed. An underspanned truss has the advantage that the lower chord is only subject to tension and the walkway can function as a compression chord on the top, which efficiently uses structural elements [3.8].

According to the above definitions and the requirements but also to the worldwide nature of the DeMoLi Bridge the pony system is selected as the most suitable solution for spans smaller than 30m and without any warnings for the desirable clearance underneath the bridge or the need of extra ramps in order to bridge the gap from the upper walking deck and the shore level. Furthermore, this type has an integrated interior railing, protecting people of failing down (they is no need for extra railing).

---

[1] The Warren truss is in fact the most popular design bridge and examples of it can be found everywhere in the world. It was patented in 1848 by its designers James Warren and Willoughby Theobald Monzani as a series of isosceles or equilateral triangles. Warren truss consists of longitudinal members joined only by angled cross-members, forming alternately inverted equilateral triangle-shaped spaces along the entire length of the bridge, ensuring that no individual strut, beam, or tie is subject to bending or torsional straining forces, but only to tension or compression. [3.10]



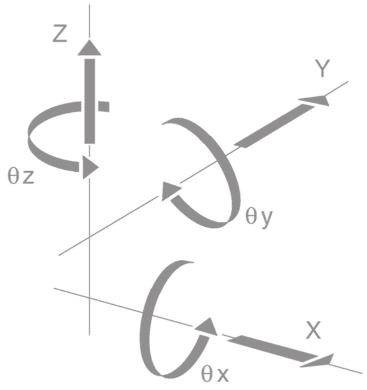


Figure 3.7 | Applications of rotation and transition as the two different types of movements [3.11]

3.2 Deployable Modular Systems

Mechanical movements can always be reduced to two basic types: rotation, translation and a combination of the two [Figure 3.7] [3.11].

Translation: In the case of linear movement, so-called translation, the position of the object in space moves parallel to the coordinate axes while its orientation remains the same.

Rotation: In case of rotation, the object changes its orientation in space by rotating about the coordinate axes while its position remains the same.

For each of these kinds of movement, one can identify three degree of freedom, depending on how the position or orientation of an object changes with respect to one, two or three coordinate axes (three dimensional displacements and three dimensional rotations). The ability of an object to move around in space is therefore defined by a maximum of six degrees of freedom (x,y,z and θx, θy, θz) [3.11].

The permitted motion is related to the number of joint's degree of freedom which is equal to the minimum number of independent coordinates needed to uniquely specify the position of a link relative to the other constrained by the joint. [3.12]

There are many movements, which can create a deployable structure and can be applied in the former Warren Pony Bridge design. The selected for further analysis are:

A. Fold: Folding Systems
B. Swivel: Swiveling Systems
C. Slide: Sliding Systems
D. Inflate: Pneumatic Systems

Furthermore, there is a variety of types according to the structural member, like struts (the basic modules are stiff 1-dimensional bars), surfaces (which are 2-dimensional elements), prestress (membrane) or pneumatic structures (consisting of flexible 1-dimensional cables and/or 2-dimensional membranes) and finally, tensegrity structures (consisting of combination of stiff rods and flexible cables) which can be combined efficiently with the above movements [3.13].

The former types of movements with existing examples and draft proposal applications in bridge construction are described in order to select the proper system that fits to the above requirements.

A. Folding System

Figure 3.3a | Folding Articulated Square Truss Mast (FAST mast) by AEC-Able Engineering in California (Warden, 1987) [3.3]

Each of the four vertical members has been fitted with three parallel cylindrical hinges, which allow it to fold within a diagonal plane. Thus, the upper square is lowered at the central hinges and the vertical members move inwards. There are also active and passive cables. The active cables are slack during folding, while they are taut and pre-tensioned when the mast is fully deployed. The two pairs of passive cross-bracing cablesare positioned on each face of the cube.

Pre-stress is applied by four fiberglass bows, which also have the function of actuating deployment of one bay of the mast.

This mast is the structure selected to deploy the solar arrays of the International Space Station.

Figure 3.3b | Folding mast by Craighead [3.13]

In 1982, N.D. Craighead et al. of Lockheed Missiles and Space Company created the 122m long, 40-bay mast composed of 3m long graphite-epoxy tubes triangulated truss, which successfully combines the mechanisms of a deployable structure with those of an efficient extended one. The requirements were reversibility, automatic deployment, avoidance of detrimental effects on extended rigidity due to the deploying mechanism and the storage of the mast, reflector and support requirements within the STS cargo bay envelope. These requirements were met by incorporating a central joint and pivoting end fittings for each longeron, as well as flexible diagonal members. Hence, the longerons were folded outside the battens while the diagonals were stowed inside.

B. Swiveling System

Figure 3.4a | The concept of pantograph [3.13]

The concept of simple pantograph with rods, pivots and hinges.

Figure 3.4b | Plane and space pantographic column based on: Triangular and square prisms [3.1]

Figure 3.4c | PDM1 and PDM2 pantograph [3.13]

The first concept (PDM1- left) consists of two parallel plane pantographs connected at relevant intervals by passive and active cables. In any configuration, angle θ is common in every pair, which allows strains-free deployment and retrieval.

The second pantographic mast (PDM2- right) consists of three of plane pantographs (six rods) lying on the side faces of a triangular prism and connected to form a triangular prism.

a: a schematic view,

b: active cables and

d: passive cables

A. Folding Systems

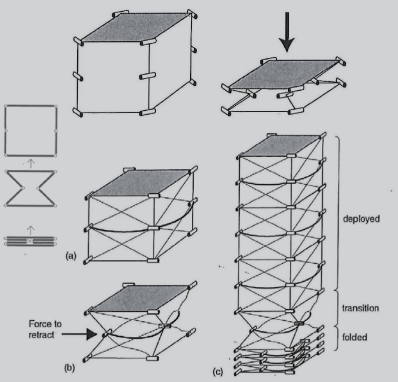


Figure 3.3a | FASTmast

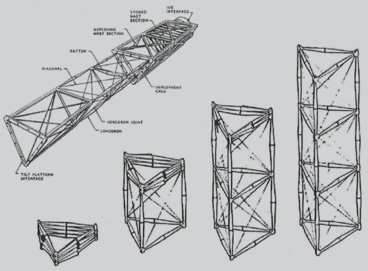


Figure 3.3b | Folding mast by Craighead

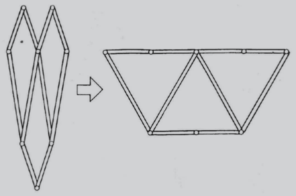


Figure 3.3c | The basic concept of DeMoLi Bridge

B. Swiveling Systems

Scissor Mechanisms

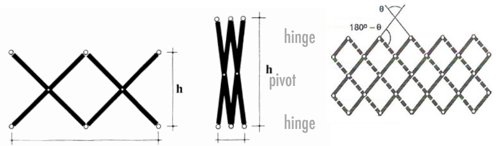


Figure 3.4a | The concept of pantograph

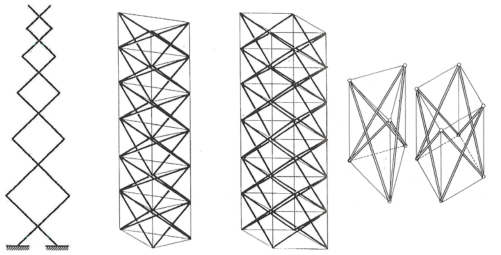


Figure 3.4b | Plane and space pantographic column

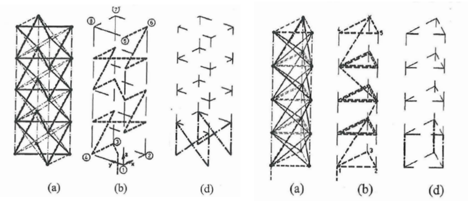


Figure 3.4c | PDM1 and PDM2 pantograph

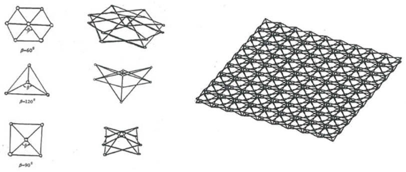


Figure 3.4d | Form units with plan view of regular polygons

3.2.1 Folding System

Folding or hinged-collapsible mechanism is formed by a set of bars or panels with hinge connections at their ends that allows the structure to be folded and extended [3.14]. Thus, it can be collapsed and expanded like an accordion, which is made out of rigid, straight elements joined by movable connections along its edge [3.15]. When the structure consists of a series of rectangular panels connected by cylindrical hinges on parallel edges, in the packaged configuration these panels stack alongside the support structure, like a curtain. This is the simplest version of the folding movements, where in its compact configuration it forms a flat structure. Such an arrangement of panels is called a concertina [3.3].

After the structure reaches its final open configuration, hinges that connect two elements lock, and then the whole system behaves as a single continuous piece. [3.1]. The locking can be achieved for instance by the use of cables or flexible elements [Figures 3.3a-b].

For all this process, there is no need for special and large equipment or tools.

According to Mobius, the problem of equilibrium system of bars and their hinges follows the equation $m= 2j-3$ in one plane and $m=3j-6$ for three-dimensional systems, where j are the hinges and m is the number of the bars [3.7].

B. Sliding Systems

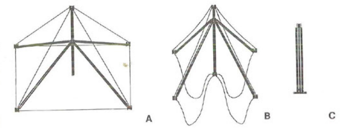


Figure 3.5a | Umbrella-like deployable basic unit

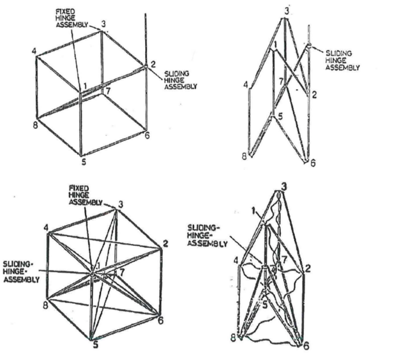


Figure 3.5b | The spatial diagonal-stiffened truss (SDT)

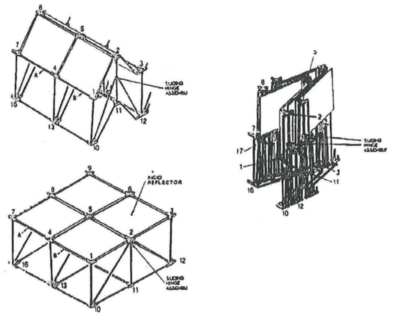


Figure 3.5c | Deployable structure with flat reflectors

B. Pneumatic Systems

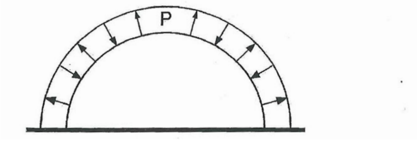


Figure 3.6a | Principle of air inflated membrane

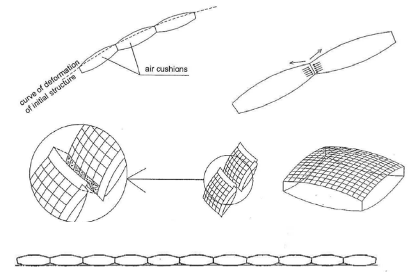


Figure 3.6b | Air cushions with tape connection

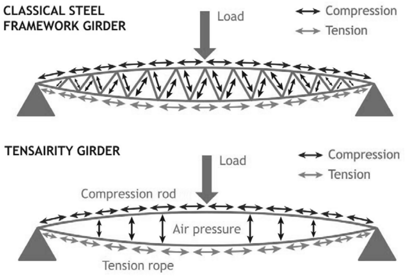


Figure 3.6c | AIR-BRIDGE

C. Sliding System
Figure 3.5a | Umbrella-like deployable basic unit [3.14]

Figure 3.4a | The spatial diagonal-stiffened truss (SDT) [3.13]
In 1989, the strong demand for special deployable structures with adequate packaging efficiency and a small number of lock mechanisms led Takamatsu and Onoda to the development a new types of deployable concepts for antennas: The spatial diagonal-stiffened truss (SDT). In SDT, six nodes have to be fixed in order to become stable. In the folded state, the sliding hinge, to which the diagonal member is connected, is away from its node and the deployment motion initiates by the downward movement of the hinge toward the node. By combining four of these modules, which share a single sliding hinge, the number of mechanisms per modules drops to 0.25. Due to the relatively small number of diagonal truss members, the structures should be considered as partially stiffened. However, if a pair of tension wires is added to both the upper and lower faces to it, the dynamic characteristics for SDT are highly improved without deteriorating the package efficiency or the number of mechanisms.

Figure 3.5c | Deployable structure with flat reflectors [3.13]

D. Pneumatic System
Figure 3.6a | Principle of air inflated membrane [3.13]

Figure 3.6b | Air cushions with tape connection [3.16]

Figure 3.6c | AIR-BRIDGE by CIMNE, BuildAir, CERCA, European Union [1.7]
Inflatable, ultra-lightweight, fast-deployable bridge for surface transport vehicles, which utilizes low-pressurized air filled beams as the primary load bearing structural spanning.
TENSAIRITY= TENSION + AIR + INTEGRITY

3.2.2 Swiveling System (based on scissor mechanisms)

Swiveling hinges have a single degree of rotation freedom and are used to connect flat building elements along one edge so that they can swing [3.11]. Scissor-Like-Elements (SLEs) are "X" arranged struts (x-structures) which are an assembly of two straight rods of equal length with swiveling hinges at the ends and pivot connections at their intermediate points, which does not restrict their relevant rotation. [3.14] Hence, each rod has three nodes, one at each end, connected to the end node of the next member through hinges and one at the intermediate point, connected to the intermediate node of another member by a pivotal connection. The pivot, or the scissor joint as call it [3.3], allows free rotation- swivel movement- between the two bars about the axis perpendicular to the plane of the pantograph, but restricts all other degrees of freedom while the hinged connections at the end point allow flap movement between the elements [3.13].
The concept of scissor-mechanisms is modular and theoretically infinitely extendable. However, the loadbearing capacity of a scissor mechanism is not optimal due to the fact in this case the pivoting hinges experience high bending moments that inevitably result in more sturdily dimensioned structural components, instead of the struts or flat elements with its plane parallel to the swiveling movements [3.11].
Three different configurations following the swiveling mechanisms are described:
1. When several SLEs place among a straight line form a planar pantographic beam- pantograph [Figure 3.4a] [2.3]. Combining two of these planar pantographs in a preset distance according to the width of the bridge, the basic foldable truss

structure consists of two parallel trusses with the deck between them is formed. As each truss consists of struts or flat planes there are several disadvantages relevant to the stability of the final structure.

2. Another scissor-like technique is a 3-dimensional scissor structure, compromises three or more primary constituent units of SLEs (x-structures) creating triangular or squared prismatic shapes [Figure 3.4b and 3.4c]. Each unit consists of two rigid diagonal members, which are the diagonals of a triangular or quadrangular lateral face of a solid. At least three minimum components are connected to each other to form the unit and the final shape.

This type of structure works like mechanisms during its entire process and therefore a locking system is necessary. One of the most active researchers in the field, S. Pellegrino, presented in 1991, a new type of deployable mast, which uses a deployable backbone and consists of rods or plates that can be folded or deployed strain-free by active and passive cables[2] [3.2].

The combined use of active and passive cables made him to develop a new type of deployable structure, which remains essentially stress-free in all folded and partially-folded configuration but can lock themselves into the fully-deployed state [3.2]. Extending the method of active and passive cables in three dimensions, 3-dimensional pantographs came up, which belongs to the category of tensegrity structures[3].

If we connect these system in such a way to guarantee the compatibility of the movement of each piece, we obtain a complex system able to grow in two or three spatial directions (deployment occurs in length or in both length and width) [3.1]. The geometric complexity increases considerably when the movement itself is three-dimensional however there are several benefits such as a more compact shape. In that way the structure is designed with maximum packing efficiency.

In general, the main disadvantage of the above system is its structural complexity. Moreover, it suits only for deck truss and thru truss types of roadbed, which are rejected as it was explained before.

3. Finally, several SLEs can be also connected to each other in order to form units with plan view of regular polygons [Figure 3.4d]. The sides and radii of the polygons are SLEs. Each side of the polygon is a symmetric SLE and each half-diagonal a non-symmetrical one [3.13]. The structure is prefabricated space frame consisting of straight bars linked together in the factory as a compacted bundle, which can then be unfolded into large-span, load-bearing structural form. During the deployment, at intermediate geometric configurations, incompatibilities between the member lengths lead to the occurrence of strains and stresses resulting in a snap-through phenomenon that "locks" the structure in their deployed configuration[4] [3.13]. These structures are suitable for deck and thru truss type of roadbed.

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2. The active cables follow chosen routes inside the backbones with the help of small pulleys. Active cables connect points whose distance decreases during deployment. Thus, they link joints that get closer during deployment; shortening these cables will then cause the pantographic to deploy. When the backbone is folded, the length is maximized and vice-versa. Unlike active cables, passive ones have constant length, approximately equal to the distance between these joints in the fully deployed configuration, and connect two points whose distance increases during deployment. The maximum distance of these two points cannot exceed the length of the passive cable, which becomes taut upon full extension. Therefore, these are taut when the backbone is fully deployed and slack when is partially or totally folded. [3.13]

3. "*Tensegrity systems are spatial reticulated systems in a state of self-stress. All their components are rectilinear. Tensioned elements have no rigidity in compression and constitute a continuous set, while compressed elements have no rigidity in tension and constitute a discontinuous set*". [3.13] This minimizes the number of members, which needs to sustain compressive forces creating lighter-weight and more transparent structures. The term "tensegrity" was coined from the phrase "tensional integrity" by Fuller, who proposes that the method could be applied to large architectural domes. [3.13]

4. The structure must be stable and free of stresses in both its compact- folded and final- deployed form. Only during the deployment process some of the members bend in order to maintain compatibility. The member stresses increase gradually and after reaching a peak value, drop and return to zero at full deployment. The strain energy that has build up in the members during deployment is released by a snap-through "clicking" into the self-sustained, stable form of a load-bearing structure, with no residual internal stresses. Once deployed, such structures are stiffened by restraining boundary nodes. [3.13]

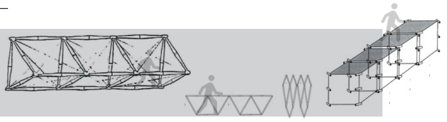
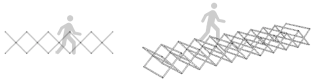
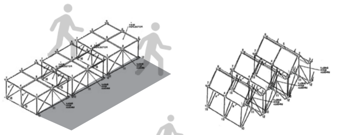
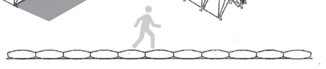
SYSTEMS	compact (packing)	lightweight	simplicity	stability	durability	efficiency	
01. Folding	60%	▮▮▯▯▯	▮▮▮▮▮	▮▮▮▮▯	▮▮▮▮▯	▮▮▮▮▯	
02. Swiveling	70%	▮▮▮▮▯	▮▮▮▯▯	▮▮▯▯▯	▮▮▯▯▯	▮▮▯▯▯	
03. Sliding	70%	▮▮▮▯▯	▮▮▮▮▯	▮▮▮▯▯	▮▮▮▯▯	▮▮▮▯▯	
04. Pneumatics	90%	▮▮▮▮▮	▮▯▯▯▯	▮▯▯▯▯	▮▯▯▯▯	▮▯▯▯▯	

Figure 3.8 | Evaluation of the four Deployable Systems

3.2.3 Sliding System

Sliding Systems are mechanisms that supported by a mast that open and close by sliding arrangements. These kinds of structures are also known as umbrella mechanisms [Figure 3.5a]. The basic unit is a deployable tetrahedron forms by 5 poles, 4 of those can move along the fifth through a node and four cables that the canvas is reinforced. When the central joint is released and it moves up along the central pole, the cables are also released and the external poles rotate toward the center pole, reaching a compact form. By moving the central node down it will return to the open tetrahedral form.

This basic unit can be altered by keeping the same principle and combined in large group to form a whole structure as it is shown in Figure 3.5b and 3.5c. [3.14] .

Sliding system concept could be applied as a solution for deployable bridges but it seems suitable for deck and thru truss type of roadbed.

3.2.4 Pneumatic System

Pneumatic structures can be transformed into three-dimensional objects by inflating them with air under pressure [3.11].

In general, inflated structures are light, rapid deployed and present reversible behavior after failure. Inflation causes tension prestressing in the walls of the structure. This prestressing is proportional to the pressure, and ensures important and quite surprising mechanical strength.

Pneumatic structures can be divided into two groups. In the first, the structure is made of a single layer fabric cover kept in position by means of increasing air pressure inside the object above the atmospheric. Structures of the second group, which is the research focus, consist of large-scale tubes made of fabric and the air pressure in each tube is supplied separately [Figure 3.6a] [3.4].

Although most of pneumatics structures are based on one module (monolithic), there is also the option of many smaller “pneumatic cushions”, which can be connected together on the borders by tape connectors following the term of modularity [Figure 3.6b].

It should notes that inflated structures have typically a short lifetime as well as low loadbearing capacity.

Figure 3.8 illustrates an evaluation of all the explained systems. The folding system although it seems undesirable solution due to its low compact capacity and its high weight, is the selected one. The reasons lie, firstly to the efficient combination with the chosen truss system and secondly, to its high range of stability and durability with low complexity.

3.3 Proportions and General Dimensions

DeMoLi's form consists of two parallel trusses, which are its main longeron beams and according to Pony truss concept the deck is located at its bottom chord. It has a standard net width of 3000mm; the height of each truss is 1300mm according to the railing bridge regulations, while it is capable of spanning gaps from 5,00m to 20,00m with length that varies from 6,00 to 21,00m by adding and subtracting modules.

The proposal design starts with a basic building block, which is an equilateral triangle with rigid structural elements forming the boundaries of it [Figure 3.9]. The Warren Truss uses equilateral triangles to spread out the loads on the bridge and each side of the triangles has the same length. This marked an improvement over the older Neville truss, which did not use equilateral triangles but isosceles ones. The triangle is considered a self-supporting shape and due to the fact that the height is 1300mm, its three sides have 1500mm length[5]. The truss structure is formed by joining the structural units in such a way that there are no duplicated faces when combined into a larger structure. The length of the bridge is increased by adding two members one horizontal and one diagonal creating the second building block and so on. Finally the width of each truss is defined later in Design Verification Phase, equal to 500mm.

Consequently, the deployable truss structure is obtained by connecting N structural units, with 1500mm length each into a chain configuration creating a deployable articulated truss. By multiplying this length of the unit N times the desired length for specific span is achieved. Therefore The minimum number of structural units is 4, which form a bridge with a length of 6m (DeMoLi6), while the maximum one is 14, forming the DeMoLi21 Bridge. Each different bridge length has also a different identity, which is defined as DeMoLi plus the length (x). Consequently, the default identity is *DeMoLix* and then it is developed as DeMoLi6, DeMoLi7.5, DemMoLi9 and so on until the DeMoLi21 but increasing the number "x" per 1.5, equal to the length of each building block [Figure 3.10].

3.4 Folding Process

The objective to the present invention is to provide a structure and more specifically a Warren Truss able to fold synchronously. The study of the deployment process is the most challenging phase, and poses severe constraints on what can or cannot be realized. Therefore, it is important to approach the field with a simple concept on theory. That's the reason of choosing the folding method made of 2-dimensional surfaces.

The focus here is what kind of movement the links of the building blocks are subjected to.

Typically, a Warren truss is composed of horizontal and diagonal elements with hinged connection in their both sides allowing them to move freely. In DeMoLi solution, each triangle is constructed of four structural members. The two of them are the diagonal sides of the triangle, which lies at 60 degrees when they are fully deployed. The other two are derived from the third horizontal side of the triangle, which is split. All the members are fitted with parallel cylindrical hinges at their both ends, which allow them to fold within a plane perpendicular to their surfaces.

The horizontal elements from both upper and lower chord are moving upward in order to fold, dragging also the diagonal webs, which are connected to the same hinges. This illustrates the kinematics involved in the packaging operation of the bridge. [Figure 3.11]

More specifically, the movement can be described by the combination of the two basic types of mechanical concepts: rotation and translation, which creates a single-folding mechanism defined only by the single parametric angle θ, able to fold

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[5] According to the Pythagorean theorem x2= (x/2)2 +13002, each side has to be 1500mm.

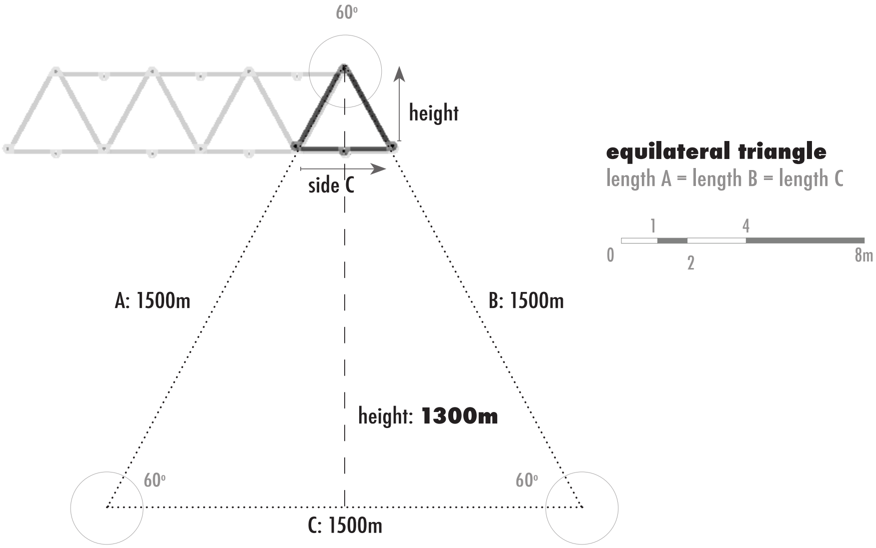
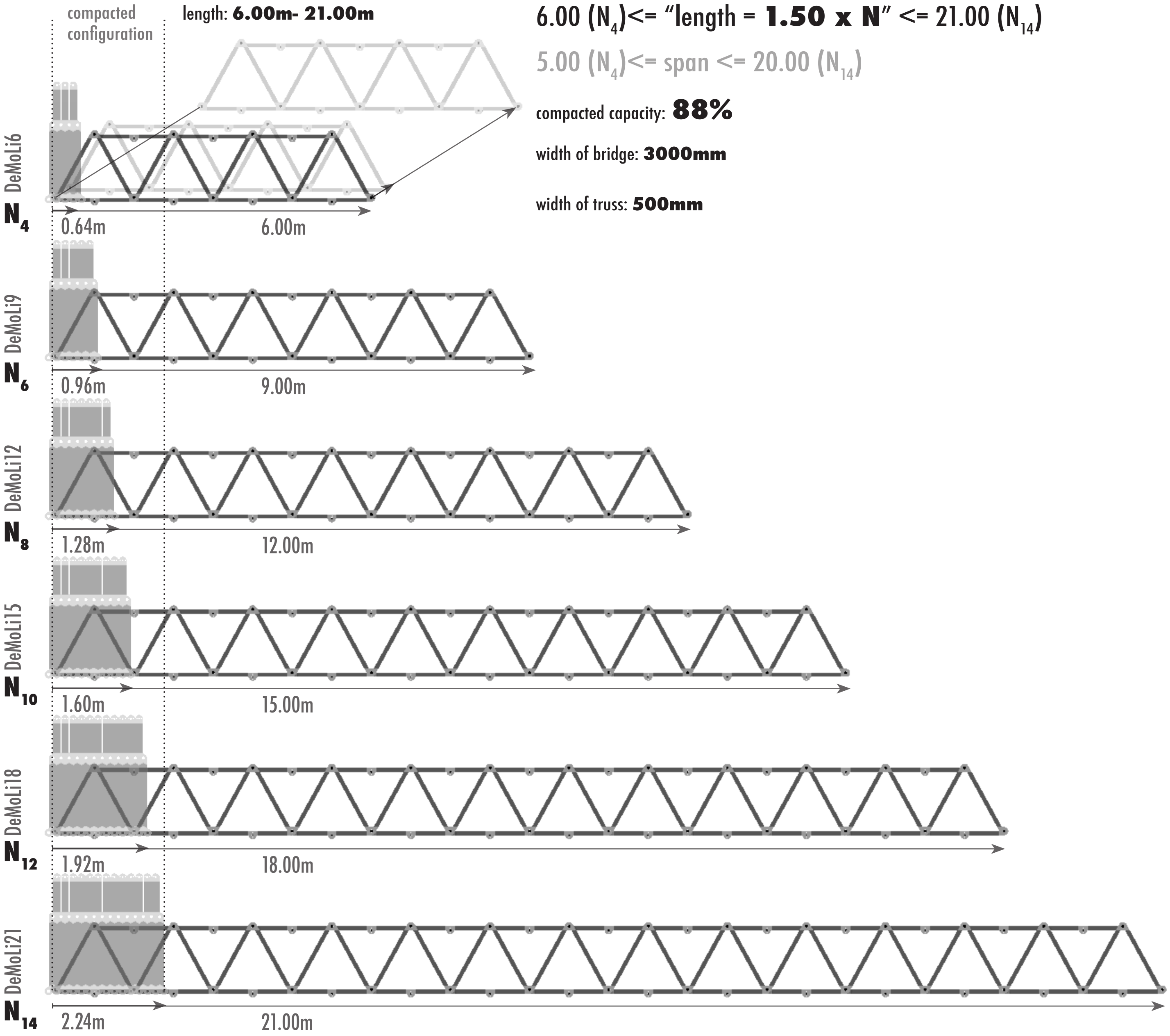


Figure 3.9 | General dimensions of one structural unit- module



6.00 (N_4)<= “length = **1.50 x N**” <= 21.00 (N_{14})

5.00 (N_4)<= span <= 20.00 (N_{14})

compacted capacity: **88%**

width of bridge: **3000mm**

width of truss: **500mm**

Figure 3.10 | Different length configurations from DeMoLi6 to DeMoLi21

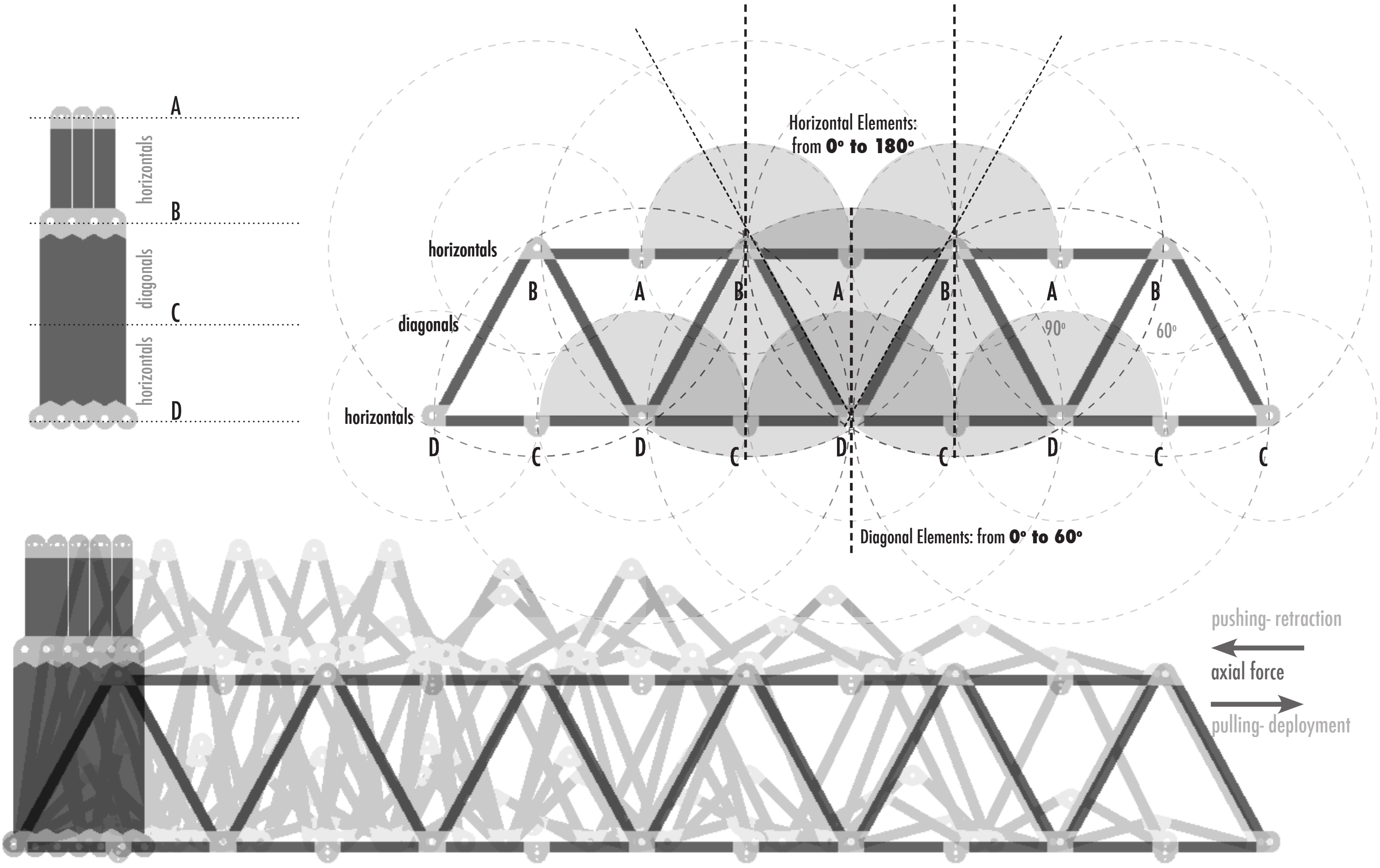


Figure 3.11 | Folding and Deployment processes of truss structure.
Scale | 1:50

Figure 3.11 | Folding and Deployment processes of truss structure.
The structural elements, both horizontals and diagonals, in the initial and final deployed configuration are displayed in solid colours, while the semi-transparent picture represent the motion of the members during deployment and all the intermediate displacements.

in planar sections having one-degree of freedom. The hinged connections allow a relatively rotation of the surfaces sufficient to extend and fold freely. If several modules couple together, the parameter θ has the same value for all them. Hence, the entire structure consists of only one mechanism which is deployed synchronously. The angle θ and the relative distances between the joints are increased during deployment and relatively they are reduced during folding.

The opening-closing mechanism works by applying an axial force along the longitudinal axis. For the deployment process from its compacted configuration, the structure is pulled while the angle between the horizontal increases from 0 degrees to 180 degrees, and between the diagonal elements from 0 to 60 degrees respectively. By reversing the deployment sequence, the structure can be instantaneously folded into a compact bundle of parallel panels, creating a “flat”, compacted configuration where all the elements lie vertically next to each other

The deployment of all members occurs in a synchronous manner and when the structure reaches the fully deployed condition, the mid-length hinges are locked forming a rigid and self-supporting truss.

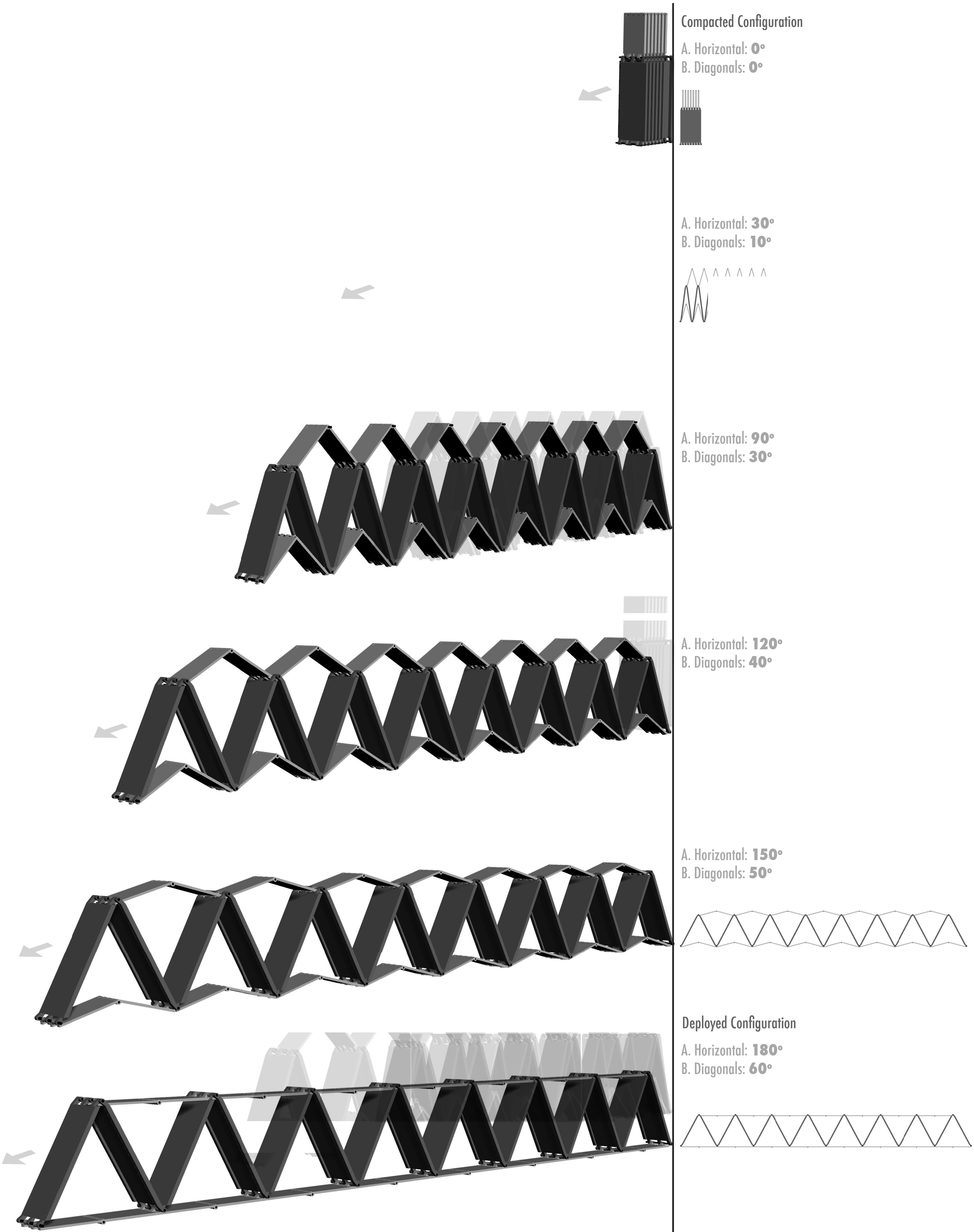


Figure 3.11 | Deployment Process of DeMoLi12 truss

4.

Design Verification

This is a product development and refinement phase, which includes extensive testing, validation and optimization in many levels based on several parameters like requirements vs cost.

Normally it involves assembling and testing prototypes through different scale mock-ups and afterwards the implementation of any required changes to the designs. However, in DeMoLi Bridge, Finite Elements Analysis (FEA) is used to refine the geometry and define the materials of the bridge and its individual components through satisfactory numerical calculations that accurately simulate mechanical behaviors such as deflections and stresses.

Starting with the definition of different load cases, proportions and materiality of the truss and the deck panels are finalized and verified. After these, the structural behavior of the final version of the bridge is presented through Diana software.

4.1 Finite Element Analysis (FEA)

Every bridge should be built in such a way that it will sustain the actions and influences upon it and remain fit for use during its intended life following the trilogy of: *Safety, Serviceability, Durability.* This means that it must have certain strength and stiffness being safe and durable over time. The above aspects have to be combined with lightness and economy as two basic design requirements of DeMoLi Bridge.

The parameters that influence the state of a structure are mainly two: the magnitude of the loads that impinge on it, as they are called the load effects, and the resistance or the strength of structure's component relevant to applied materials and geometry. If the load effects exceed the allowable resistance, then the component fails. [4.9]

Design Verification Phase has four objectives, which are also the subdivisions of the chapter:

1. Firstly, to *clarify the applied loads* according to the design requirements,
2. Secondly, to *optimize the overall dimensions* of the structure,
3. Then, to *choose the "right" combination of materials* for a lightweight and cost-efficient solution, and
4. Finally, to *review the structural behavior* of the bridge, based on the selected materials and forms, providing a satisfactory numerical model that accurately simulates its mechanical behavior and check it in accordance with the reliability approach.

During the design of DeMoLi Bridge, Finite Element Analysis (FEA) through Karamba plug-in but mainly Diana software is performed through a two-prong modeling procedure. Due to the symmetrical structure, the first model refers to one truss as a two-dimensional model made of linear truss elements. The second model is related to the deck and given that the bridge consists of identical self-supported panels only one of them is tested, which is made of surfaces creating a three-dimensional object. In both of them, the process includes the following steps: geometry generation, loads, material properties and supports definitions and finally the results of the analysis and serviceability checks.

Due to the worldwide (international), deployable and emergency character of the bridge, the overall concept related to Design Verification Phase, from load definitions (choice of the design loads) to the development of the limit states format is based on a hybrid of principles and rules set out by three different bridge regulations. The first one is the AASHTO, American Association of State Highway and Transportation Officials (Standard Specifications for Highway Bridges, 17th Edition- 2002) [4.2], the second is the Eurocodes (more specifically National Annex for EN 1990 Annex A2 (application for bridges)[1], EN 1991-2 and EN 1999) [4.1.7&8] and finally, TCTD, Trilateral Design and Test Code for Military Bridging and Gap-Crossing Equipment [4.3].

4.2 Load Cases

"Is the structure efficient or not for its purpose?"

To answer this question all the loads that are applied to the structure must be defined.

A bridge is a structure used to carry loads[2] over an opening. There are several senses in which the term "load" may be qualified, such as in the terms of "service", "design" and "legal" loads [4.9]. The focus here is on the second category, since the choice of the design loads is important for the selection of the material and the dimensions of all the members[3].

In general the design loads include [4.9]:

1. Self-weight of the structure,
2. Vehicle weights,
3. Horizontal vehicle loads, such as those due to braking or centrifugal force,
4. Dynamic vertical loads, caused by dynamic interaction between primary service vehicles and the bridge,
5. Pedestrians weights,
6. Loads applied by vehicles or pedestrians to railings and kerbs,
7. Natural loads, such as stream during flood, wind, earthquake and thermal effects.

The former five are analyzed and calculated in the following pages, while the latter two are just mentioned and they are considered as further development steps. In general, loads are divided into permanent[4] and variable[5] over time. The permanent ones are also called dead loads and include the self-weight of the bridge and all of its fixtures and fittings, while variable loads, which include live and natural loads, are many and various; some are man-made and some are natural. [4.10]

---

[1] This Annex A2 to EN 1990 gives rules and methods for establishing combinations of actions for serviceability and ultimate limit state verifications (except fatigue verifications) with the recommended design values of permanent, variable and accidental actions and ψ factors that must be used in the design of road bridges, footbridges and railway bridges. Methods and rules for verifications relating to some material-independent serviceability limit states are also given. [4.1]

[2] Loads are actions applied to a bridge.
According to EN 1990-1.5.3.1, action (F) are:
a) Set of forces (loads) applied to the structure (direct action);
b) Set of imposed deformations or accelerations caused for example, by temperature changes, moisture variation, uneven settlement or earthquakes (indirect action). [4.1]

[3] However, design loads cannot be separated for the study of the other two. The service loads are applied to the bridge during its service life and the legal limits are intended to govern these loads. [4.9]

[4] According to EN 1990- 1.5.3.3, permanent Action (G): Action that is likely to act throughout a given reference period and for which the variation in magnitude with time is negligible, or for which the variation is always in the same direction (monotonic) until the action attains a certain limit value. [4.1]

[5] According to EN 1990- 1.5.3.4, variable Action (Q): Action for which the variation in magnitude with time is neither negligible nor monotonic [4.1]

4.2.1 Permanent loads (G)

Permanent loads of the bridge include the weight of all of its structural parts, fixtures and services like deck surfacing, connection elements, kerbs, parapets, etc., which are distributed uniformly along the structure. Although most of the time the initial FEA calculations of dead loads is like the chicken- egg problem, the weight of the structural parts has to be assumed at the first instance and subsequently confirmed after the structural design is completed when the self-weights of all of the components are known.

This assumption is done during the first two steps for the geometry finalization (part 4.3) and the material selection (part 4.4), while during the structural analysis (part 4.6) more accurate values, related to the selected materials and shapes are set.

For the current purposes, the permanent loads are limited to the weight of one truss combined with the half weight of the deck in truss model and the weight of the defined panel in deck model[6].

4.2.2 Variable Loads (Q)

The variable loads are divided into live and natural loads. Live loads are the loads of pedestrians and vehicles, while the natural ones are related to the power of the nature such as wind, thermal expansion, earthquakes, etc. For the purposes of the current project only the live loads are calculated while the natural ones are just mentioned.

A. Live Loads

The actual loads on road bridges result from pedestrians and various categories of vehicles.

'How many people will be on the bridge at any time?'

'What is the biggest vehicle-truck that might cross the bridge?'

'How many vehicles-trucks will be on the bridge at any time?'

A.1 Pedestrian Loads

Pedestrian loading encompasses a number of forms. In presented analysis only the static load of people due to a particular density of pedestrians is calculated. The loads placed on handrails by group or crush of people require further consideration.

There are various densities of pedestrian loading. According the EN1991-2 [4.8], 1.5 to 2kPa is regarded as a domestic loading (LM1), 3 to 4kPa is usually a commercial loading and a load of 5kPa is a "crowd" loading (LM4)[7] [4.9].

Due to the emergency character of the bridge, extended usage is expected. Consequently, the bridge is tested under a uniformly distributed load from people (including dynamic amplification) of 5kPa (=5kN/m^2), which is applied on the loading surface of the deck. 5kPa is translated into 7 persons/m^2, assuming that each person weights an average of 700N (1m^2= 5000/700= 7people) [Figure 4.1.1]. It is estimated that approximately 440 people are able to be on the DeMoLi21 at any time.

A.2 Traffic Loads

Loads due to the road traffic include cars, lorries and special vehicles, like emergency vehicles, giving rise to vertical and horizontal, static and dynamic forces. Several traffic load models are given by the selected standard regulations. These models aim to reproduce the real values of the effects induced in the bridge by the real traffic.

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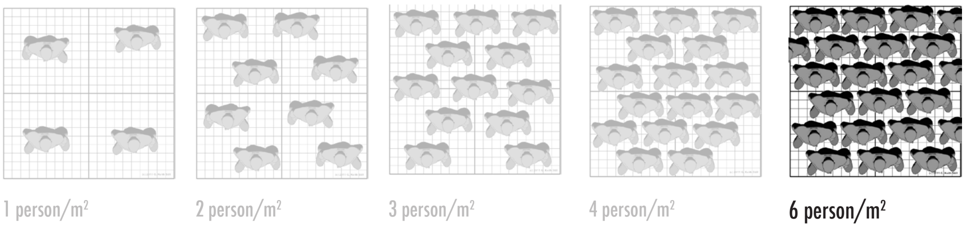
[6] FEA calculates the weight of defined structural member automatically according to the applied material properties (density) and the gravity force by using the command body force (-9810 in z-axis).

[7] Figure 4.1.1 shows various densities of pedestrians loadings: 1.5kPa= 2persons/m^2, 2kPa= 2.75persons/m^2, 3kPa=4.25persons/m^2, 4kPa= 5.5persons/m^2 and 5kPa= 7persons/m^2 [3.4]

LC1: Pedestrians, LM4: 5kPa- according to EN1991-2



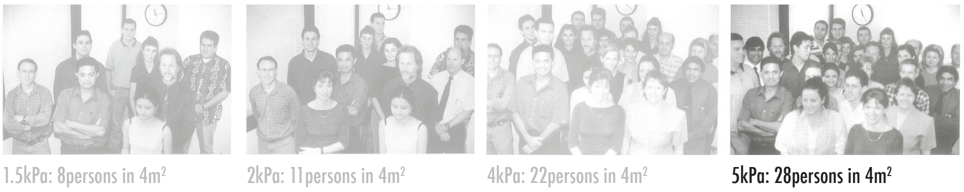


Figure 4.1.1 | Various Densities of Pedestrian Loadings [4.9]

LC2: Vehicle, LM1- according to EN1991-2

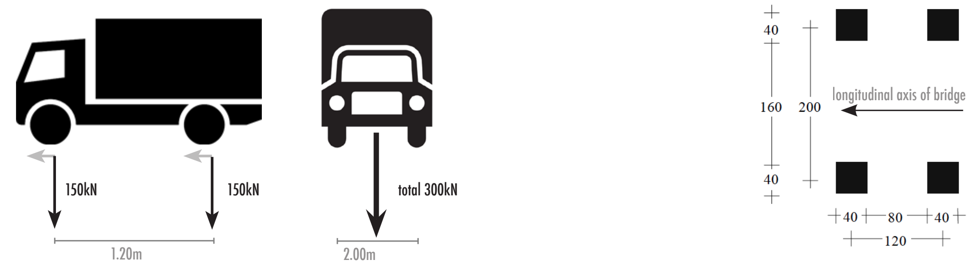

Plan of the wheels print on the deck

Figure 4.1.2 | Eurocode EN 1991-2, Highway Bridge for Loading Model 1 [4.7]

LC3: Truck, HS20-44 loading- according to American AASHTO

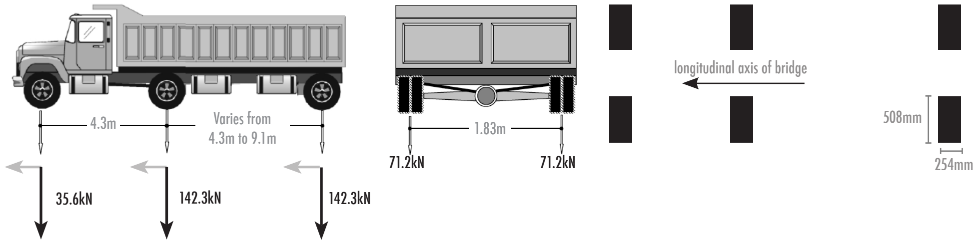

Plan of the wheels print on the deck

Figure 4.1.3 | American AASHTO for HS20-44 loading [4.2]

LC4: Tracked Vehicle, MLC40- according to TDTC

Tracked Vehicle

40.00 Tons

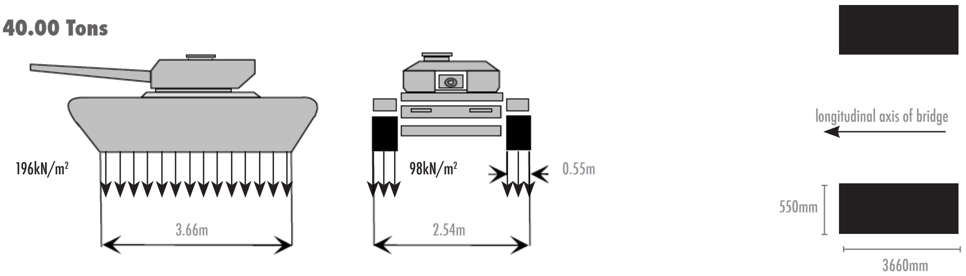

Plan of the wheels print on the deck

Figure 4.1.4 | Trilateral Design and Test Code for Military Bridging of MLC40 Tracked Vehicle [4.3]

The tested vehicle loads are the three most suitable according to the design regulations:
1. LM1 from EN 1991-2,
2. HS20-44 from AASHTO and
3. MLC40 from TDTC.
Analytically,
1. LM1 from EN 1991-2
The loading code EN 1991-2 specifies two Load Models for normal highway bridge traffic (LM1 and LM2) and one for abnormal (LM3). Model Load 1 (LM1) is intended to cover *most of the effect of traffic of lorries and cars* [4.8]. It has a double axle concentrated load of 300kN in total[8] (also called a tandem system or TS= a_Q x Q_{ik}), together with a uniformly distributed load 9kN/m^2 (UDL= a_Q x q_k). Each axle of the Tandem System (TS) with 150kN load should be taken into account with two identical wheels, the load per wheel being therefore half. The contact surface of each wheel is a square 0,40 m side length [4.8]. [Figure 4.1.2] In general, only the TS is used, which incorporates also the dynamic- impact amplification. [4.9]
Just to mention that the Load Model 2 (LM2) is a single-axle load applied on specific tire contact areas, which covers the dynamic effects of the normal traffic on short structural members. Load Model 3 (LM3) is really extreme for an emergency case, representing abnormal vehicles with six-axles and 165kN load per axle, covering vehicles for more than 100tons. Therefore, both of them are not taken into consideration.
2. HS20-44 from AASHTO
According to AASHTO specifications and 3.7.2, there are four standard classes of highway loading: H20, H15, HS20, HS15. The heaviest vehicle (36tons) is a standard HS20-44 truck. It is used for bridge supporting Interstate highways, which carry heavy truck traffic. In HS20-44 loading, the first two axles (at the left) form the H20 truck, so called because its total weight is 20 US tons. The leading axle is 4US tons (35.6kN), followed by one of 16US tons (142kN) with an axle spacing of 4.3m. This is added to the rear, semi-trailer axle, also of 16US tons (142kN) with an axle spacing that can be varied by the designers from 4.3 to 9.1m. [4.11]
The wheel print has a rectangular shape with length in traffic direction of 10inches (254mm) and width of 20inches (508mm). The pressure on the deck introduced by the tire contact areas is thus 550kN/m^2. [Figure 4.1.3]
3. MLC40 from TDTC
Due to the fact that the DeMoLi Bridge has a lot of similarities with deployable military bridges and it will be probably used from military vehicles, it is also calculated according to military load classification MLC40 for tracked vehicles. MLC40 includes a 40tons-tracked vehicle with contact surface area 550x3660mm and a distributed load of 196kN/m^2. [Figure 4.1.4]

For the calculation of the final design loads several factors must be also considered.
Partial factor
The load partial factor (γ) is applied for both live and dead loads. According to National Annex for EN 1990 Annex A2, Table A2.4 (B), which is used for the design of structural members (STR) [4.1] the partial factors are:
γ_G= 1.35, for the permanent loads (G) and
γ_Q= 1.50, for variable loads (Q),

---

[8] For many applications, it is necessary to apply an adjustment factor (the combination factor ψ) to reduce the specified loads, but it is suggested that for bridges without signs restricting vehicle weights, this factor should be not less than 0.8. Although, there will be weight and speed limitations due to the emergency and uncertainty character of the bridge a factor of 1, is used.

Load Cases	**DEMOLI:**	**21**				
A. Dead Loads (G)	Load (N)	Partial Factor (1.35)		Deck/2		
Gtruss (N)	22544	30434				
Gdeck (N)	51915	70085				
Gdeck/ node (N)		4672		**2336**		
B. Live Loads (Q)	TS (kN)	Partial Factor (1.5)	Impact Factor (1.15)	**A. Truss** TS (N)	**B. Deck** UDL (N/m^2)	Horizontal (N)
Pedestrians						
LC1. Qpedestrian- 5kPa (N)	168000	252000				
Qpedestrian/node (N)		**16800**				
Vehicles						
LC2. LM1 (double-axle)	150000	225000	-	**112500**	703125	56250
	150000	225000	-	**112500**	703125	56250
LC3. HS20-44 (three-axle)	35600	53400	61410	**30705**	238023	15353
	142300	213450	245468	**122734**	951424	61367
	142300	213450	245468	**122734**	951424	61367
LC4. MLC40 (tracked)	59334	89001	102351	**34117**	86830	3412

Figure 4.2 | Table with the four Load Cases for DeMoLi21 application

Impact Factor

The maximum vertical loads exerted by a moving vehicle will often exceed those produced by an equivalent static or slow moving vehicle. The effect has commonly been called impact, and it is expressed by the impact factor I [4.9]. To provide the impact on a bridge, the vehicle induced load, which is the vertical load, is increased (is multiplied) by the calculated impact factor I, which is given by the formula according to article 3.8.2 of AASHTO specifications:

I=50/(L+125) =<0.3,

where, L is the length of the bridge in feet.

The expression with L in meters is:

I= 15.24 /(L+38.1) =<0.3

For the different lengths of DeMoLi Bridge, from 6 to 21 the impact factor varies from 0.34-0.26. However, according to TDTC the impact factor for Assault Mission Bridges is limited to 1.15 for speed<25km/h. [1.4] Therefore, the impact factor for LC3 and 4 (since in LC2 is pre-calculated) is considered equal to 1.15.

Therefore, the values of the factored load for a strength limit states are:

1.35G + 1.75Q,

where, 1.75= partial factor (1.5) x impact factor (1.15)

Horizontal loads

Horizontal loads are also called braking and acceleration forces and they are equal to the braking factor multiplied by the vehicle dead load. It should be taken as longitudinal force acting at finished carriageway level. The horizontal live load according to 3.9 AASHTO specifications is equal to 5% of the vertical load and this value should be calculated as a fraction of the total maximum vertical corresponding to the load model. According to TDTC 5.3.8 the breaking and acceleration factor for tracked vehicles is 0.1 times (10%) the vehicle's load, V. Therefore, 0.05 is calculated in LC2 and LC3, while the factor of 0.1 is applied in LC4.

Finally, *fatigue loading* and *accidental actions* are not covered, and they are considered for further development.

Summarizing, the design value of actions F_d, caused by an action F, can be expressed in general term as [4.8]:
$F_d = \gamma \times F_{rep}$
with, $F_{rep} = \psi \times F$
where,
F: is the characteristic value of the action,
F_{rep}: is the relevant representative value of the action,
γ: is a partial factor of the action which takes accounts of the possibility of unfavorable deviations of the action values from the representative values and
ψ: is the combination factor, which is considered as 1.

Consequently, for the purposes of the current project the following loads are calculated [Figure 4.2]*:*
Permanent Loads (G):
G_{truss}*= Weight of Truss x partial factor (1.35)- vertical load*
G_{deck}*= Weight of Deck x partial factor (1.35)- vertical load*
Variable Loads (Q):
$Q_{pedestrinas}$*= 5kPa- vertical load*
$Q_{vehicle\text{-}vertical}$*= Vertical Load x impact factor (1.15) x partial factor (1.5)- vertical load*
$Q_{vehicle\text{-}horizontal}$*= 0.05 (5%) x Vertical Load- horizontal load*

B. Natural loads
Bridges are threatened by all sorts of hazards, almost all of which can be traced back to 'Mother Nature'[9]. Natural loads are all the environmental loads, like wind, flooding, changes in temperature, earthquakes, etc. Other real threats include the impacts of collisions, snow, fire, and explosions. Especially, in an emergency bridge, the impact of all these threats is much bigger and the bridge has to be strong enough to resist them.
All the variable loads, but especially the natural loads are so uncertain. They can be estimated according to the previous experiences but they can change dramatically. In case of a worldwide bridge, the calculation of all these become really complicated because the assumptions depend on latitude and longitude, local position, climate conditions, etc.
Wind Loads
Wind load is the most usual form of the above loads. It may act as:
1. Horizontally, transverse to the direction of the span,
2. Horizontally, along the direction of the span,
3. Vertically, upwards causing uplift.

Determination of wind loads on bridges where the loads would make a significant contribution is too complex for simplified rules. For bridges with high natural frequency of vibration, only the static loading effect of wind needs to be considered, while the dynamic effect of wind and the oscillation caused by it, are very important for bridges with low natural frequency, like DeMoLi design.
Wind load is not generally significant for short-span bridges like DeMoLi.
Natural frequency
All bridges and other structures, including the human body, have what scientists call a natural frequency—when objects vibrate freely. If wind or pedestrians apply forces to the bridge at the same frequency as its natural frequency then resonance occurs and vibrations can become very large indeed. Vibrations depend crucially on the fundamental frequencies of the bridge. These in turn are related to mass, damping, and stiffness—all characteristics of the materials and geome-

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[9] *Mother Nature requires respect—she will search out any weakness in a bridge, sooner or later. That is why, in the past, bridge builders have sometimes seen her as an adversary—someone to be controlled. She will inevitably find out any sign of weakness and you and your bridge will be in trouble. Now we have realized that we must learn to work sustainable in harmony with nature—but it is a working relationship that demands total regard. So, the motto is 'be prepared for the unexpected'* [4.10]

try of it[10].

Due to the fact that the bridge is light construction, the natural frequencies of bridge may fall in the unacceptable range and therefore in a further development phase must be considered. No further checks are required on vibration at serviceability if the fundamental natural frequency of the unloaded bridge exceeds 5Hz. [4.9]

In conclusion, the four load cases with analytically all the applied loads that are tested for one truss of DeMoLi21 and one deck panel are shown in Figure 4.2:
1. LC1: Full of people and uniformly distributed load of 5kPa,
2. LC2: Standard vehicle load configuration based on EN 1991-2 and the Load Model 1 with total load of 300kN,
3. LC3: The heaviest truck HS20-44 according to AASHTO with maximum 142.3kN/axles and
4. LC4: MLC40 for tracked military vehicle.

In the case of truss, due to the symmetrical geometry of the bridge, the analysis is performed just for one of the two trusses and therefore all the loads (both live and dead ones) are split. Specifically, in LC1, expect for the dead load of one truss and half of the deck, which are applied in all the load cases, there is an additional load on all the nodes, which is the distributed load from pedestrians equal to 5kPa. For the rest load cases, the load of one wheel per axle is calculated. This load is applied on the nodes in the middle of the truss based on the specified distances between the axles.

In the case of the deck panel, the applied forces are the weight of the calculated elements and the calculated distributed loads according to the defined load cases as shown in Figure 4.2.

During the geometry finalization and the material selection, in order to simplifying the process, the calculated loads are limited to the dead loads combined with the distributed load of 5kPa of pedestrians.

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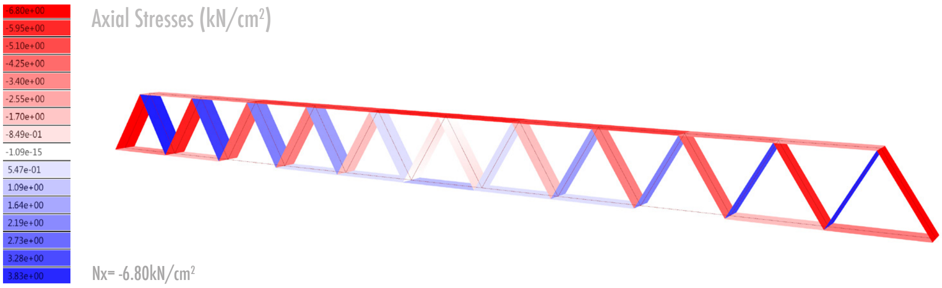
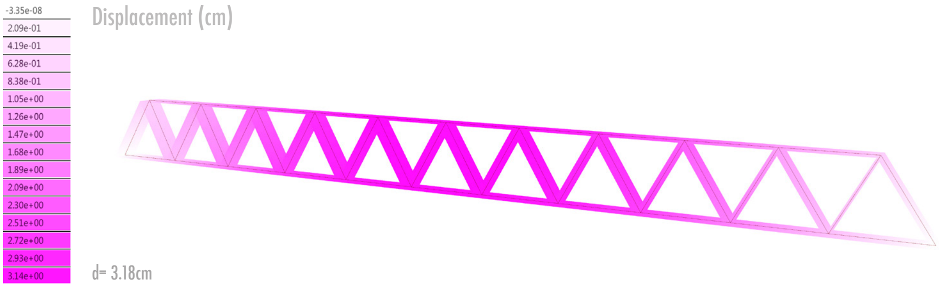
[10] Subtle interactions between the forcing frequencies and the modes of vibration, as in the flutter of the Tacoma Narrows Bridge, make this a complex matter even for specialists. [4.10]

Selected Parameters

Height of Module= 1.30m, Length of Module= 1.50m, Width of Truss= 40cm, Diagonals= 0.50cm, Horizontals= 1.00cm


Axial Stresses (kN/cm²)

Nx= -6.80kN/cm²


Displacement (cm)

d= 3.18cm

Figure 4.4 | The presented axial stresses and displacement in Karamba plug-in according to the selected parameters

4.3 Geometry Finalization

4.3.1 Truss

For the geometry finalization of the truss, Karamba, a parametric structural analysis plug-in for Grasshopper, is used, keeping the model geometrically flexible and allowing shape optimization by changing its dimensions. The goal of this analysis is to optimize the geometry of the truss based on the structural behavior of the bridge.

The process of Karamba analysis is divided into three parts. Firstly, the parametric geometry is defined using Grasshopper. Then, multiple inputs for Karamba analysis are set. These are related to materiality, cross sections, supports, boundary conditions and loads. Finally, the results from the structural analysis are visualized.

The parameters refer to the whole structure (its overall length which varies from 6 to 21m, its width, which is 3.00m and the deck thickness) as well as to the triangular module. The latter are the length of the horizontal side of the triangle, the module's height and the thickness of both the horizontal and diagonal elements. Through these parameters, both the geometry and the cross sections of all the elements are parametrically defined.

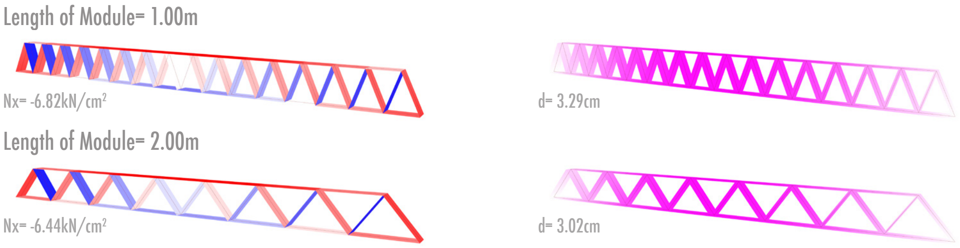
In order to simplify the calculation of the structure, the geometry of the truss bridge is translated into a simple Warren Truss. Furthermore, the elements are grouped into diagonal and horizontal made of the same material property (aluminum). For simplification purposes during the analysis, the cross sections are illustrated as solid sections made of aluminum.

The bridge is considered clamped to the one side and pinned to the other. The applied loads are the dead loads from one truss and from half of the deck combined with the distributed load of people (5kPa), which is applied to half of the deck's width.

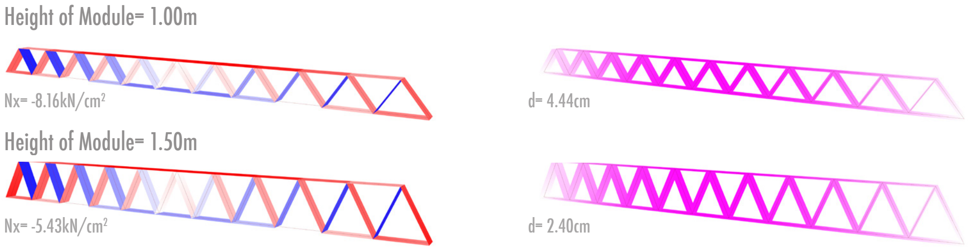
For the initial calculation some values, such as the elements' thickness and several dimensions of the structure, are assumed in order to depict the first results. Then, according to these results, input is re-adjusted and new values are calculat-

Axial Stresses (kN/cm^2) Displacement (cm)

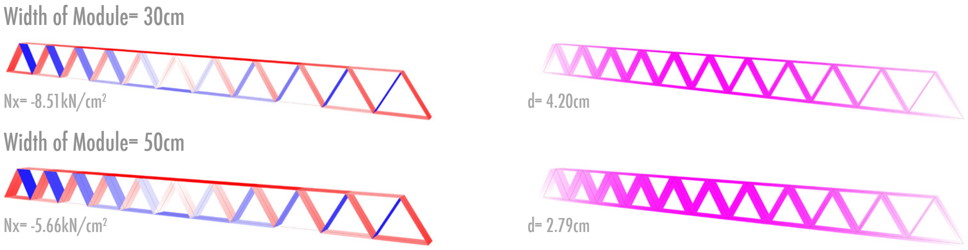
A. Length of Module



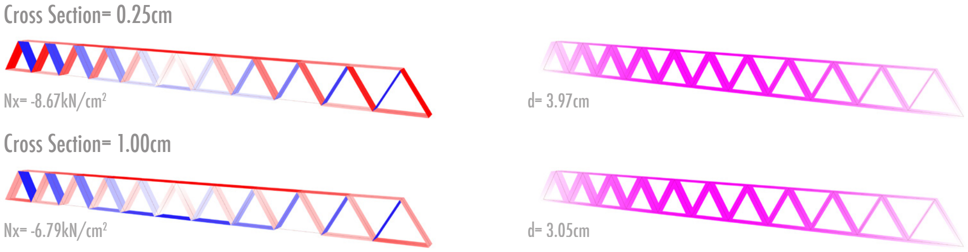
B. Height of Module



C. Width of Module



D. Cross Section of Diagonals



E. Cross Section of Horizontals

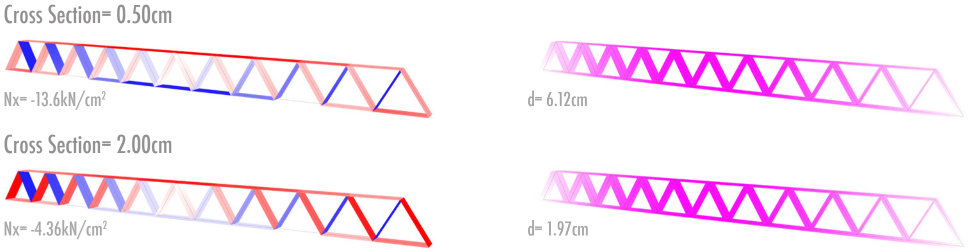


Figure 4.3| The influences on stresses and displacement by changing parametric values in Karamba plug-in

ed. Repeating the described process, a continuous optimization of the structural geometry is succeeded.

Figure 4.3 shows different attempts and their Karamba structural analysis results for DeMoLi21 by changing five parameters. These are the height, the width and the length of the triangular modules and the cross sections of the horizontal and diagonal elements. During this procedure, the first check refers to the stresses, which need to be within the allowable levels. Provided that the stresses are approved, the further concern is the achievement of minimum displacements combined with a lightweight and handy structure. As it is shown in the same figure, some parameters influence significantly the behavior of the structure (such as the height and the width of the truss and the cross section of the horizontal elements), while some others (like the length of the module and the cross section of the diagonal elements) do not cause considerable changes.

The final values of the parameters and their structural results are shown in Figure 4.4.

4.3.2 Deck Panel

Comparing Diana software analysis results with four different cross sections, which form multi-voided hollow orthotropic bridge decks, carries out the geometry finalization for the bridge's deck. All the elements of the compared sections have the same properties, flat shells of 5mm thickness made of aluminum, which form the deck panel with dimensions of 1.50m x 3.00m x 130mm. The calculated loads are the dead load of each section plus a uniformly distributed load of 5kPa, which is applied on the upper flange of the panel according to LC1. Furthermore, all of then are pinned to the four corners of the deck's panel. Since the design stresses follow the allowable stresses, the focus is on the displacements that occur under the above loads.

Figure 4.5 presents the four cases together with their relative displacements. The first three ones deal with the density of the diagonal and vertical elements inside the deck panel. As it is expected, by increasing the density the element, the panel continues to behave in the same way, however the displacements are less. Although, this seems to be an advantage of the structure, the final weight, the fabrication complexity and the cost must be also considered. Since the presented displacements are not significantly improved, by increasing the elements of the cross sections, but instead the weight and the price are changing considerably, the selected form out of the three is the section with the least diagonal and vertical elements (Case C).

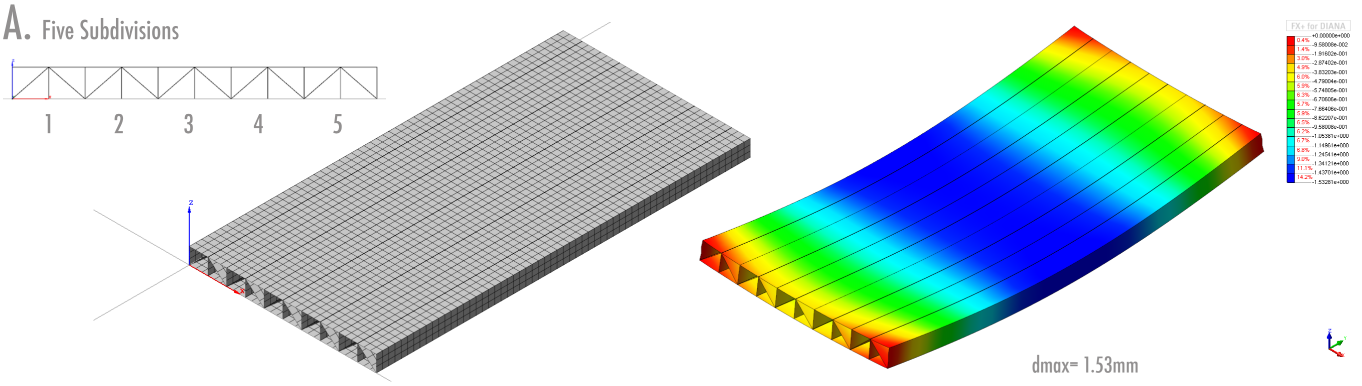
Adopting the concept of placing material where it will be most efficiently used, a forth case based on the latter cross section is presented. This keeps the same density of three triangular units, but the vertical elements where the diagonals have an upward direction are eliminated. As the displacement's influences according to this solution are slightly increased but the final weight and the fabrication process are improved (less weight and less hollow voided), it seems to be the best solution regarding to the requirements of weight and cost.

Specifically, the deck panel consists of three identical sections that are welded together in order to form the final deck's panel. Each of these sections consists of upper and lower flanges, two diagonal elements that slant downwards and two vertical members at their both ends.

Geometry

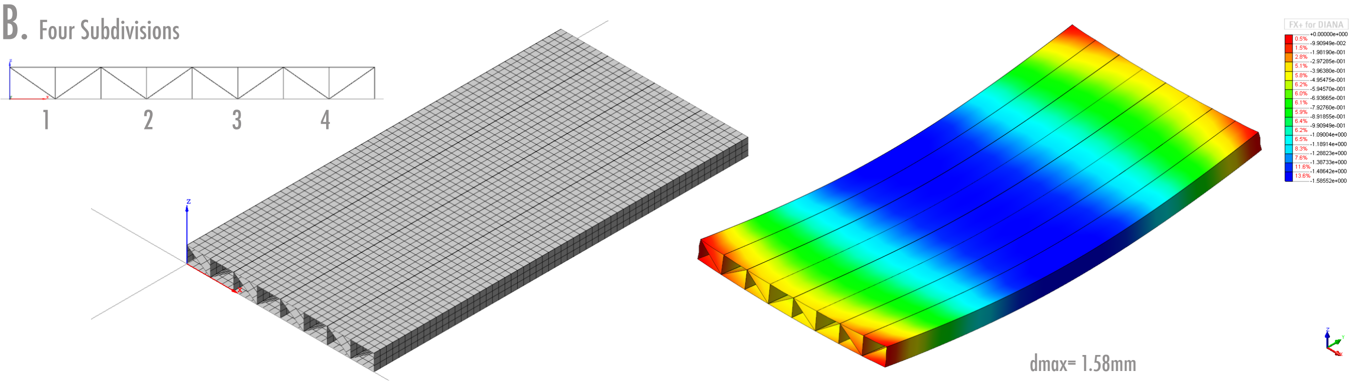
Displacement- DtZ (mm)

A. Five Subdivisions



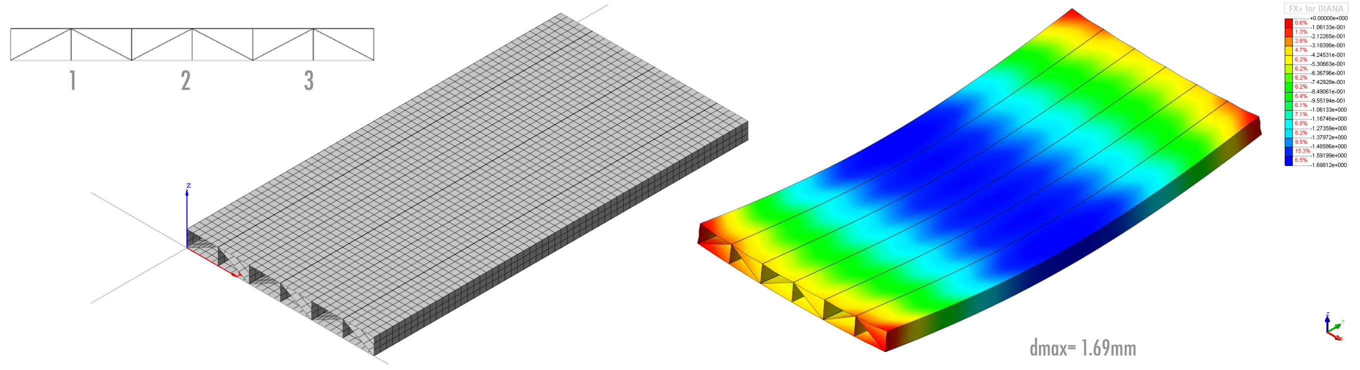
dmax= 1.53mm

B. Four Subdivisions



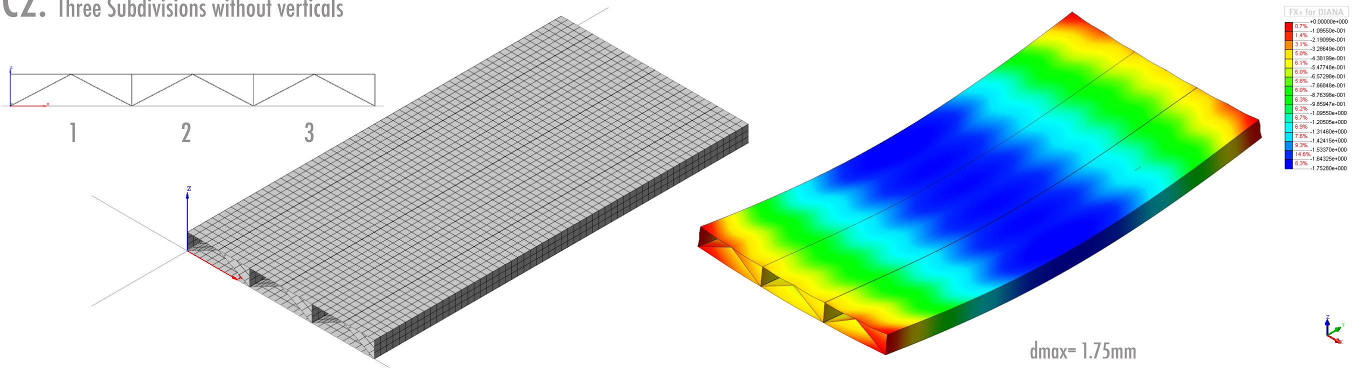
dmax= 1.58mm

C. Three Subdivisions



dmax= 1.69mm

C2. Three Subdivisions without verticals



dmax= 1.75mm

Figure 4.5 | The four compared cross sections and their related displacements through Diana software

4.4 Material Selection

This part deals with the comparison of the three materials that were selected during the Concept Design Phase and the choice of the “right” ones for both truss and deck panels. The tested materials are aluminum 6061, GFRP and CFRP[11].

The required data for the Diana material definition are: Young’s Modulus, Poison’s ratio, thermal coefficient and finally density. These properties for the compared materials are shown in Figure 2.16.

The process for the material selection is similar to the geometry finalization one. Although the previews selected geometry is tested, by applying different materials, changes to the thickness of the elements are necessary in order to achieve the same deflection under a uniformly distributed load of 5kPa. In all design situations, no relevant limit states are exceeded.

The selected materials are evaluating according to their final weight but also the price, as there is a need for a lightweight and cost-efficient solution by doing a structural analysis through Diana software. Out of comparison, two graphs, one from the truss and another from the deck panel, with the parameter of weight (kg) and price (euro) in x and y-axis respectively are presented [Figure 4.7].

4.4.1 Truss

The geometry in Diana software for the truss is divided into the hinged connections (at each corner of the triangle and at the intermediate points of the horizontal elements), the horizontal and diagonal elements. All of them are one- dimensional truss elements. In general, for the hinged connections, aluminum is used in all different cases.

Applying the load of 5kPa, the goals is to achieve a displacement of approximately L/350= 6mm for all the compared materials.

GFRP presents really disappointing results because both its price and weight are extremely high. This results from the low Young’s Modulus of the material. As it is seen, the low Young’s Modulus, has essential consequences for the geometry and the weight of the design, since deflections, lateral buckling and local buckling directly depend on the elastic modulus. [4.12] Although its density is lower than aluminum, it weights 2 times up and it is 25 times more expensive. This is an example that light objects shouldn’t always made by the lightest possible materials.

Evaluating the two parameters of price/weight and the presented data from Figure 4.6, it seems that in current emergency solution, the aluminum seems to be “right” material. It is ten times cheaper and less than two times heavier in comparison with CFRP. Although, it is the material with the highest density, its mechanical properties in combination with shape performance and price, make it the best solution according to the design requirements.

4.4.2 Deck Panel

The results from the material comparison for the deck panels resemble to the truss ones.

In order to achieve the same displacement, the thickness of GRFP flat shell elements must be increased 2.5 times in comparison with aluminum and CFRP.

Specifically, comparing the weight of aluminum and GFRP panels:

Aluminum: 2mm

GFRP: 5mm

However, the important aspects in proposal design are not the thickness as a number but the overall weight and then the cost.

---

[11] The applied properties for the tested materials according to CES EduPack encyclopedia are:
Aluminum: Elastic Modulus: 69800 N/mm2, Poisson’s Ration: 0.33, Expansion Coefficient: 2.4e-05, Mass Density: 2.7e-09 N/mm3/g, Shear Modulus: 26240N/mm2
GFRP: Elastic Modulus: 20000 N/mm2, Poisson’s Ration: 0.314, Expansion Coefficient: 2e-05, Mass Density: 1.7e-09 N/mm3/g, Shear Modulus: 7610N/mm2
CFRP: Elastic Modulus: 69000 N/mm2, Poisson’s Ration: 0.305, Expansion Coefficient: 0.002, Mass Density: 1.5e-09 N/mm3/g, Shear Modulus: 26436N/mm2

Material	horizontals		diagonals		Density (kg/m^3)	Weight (kg)	Price (euro)
	Cross Section (mm^2)	Thickness (mm)	Cross Section (mm^2)	Thickness (mm)			
CFRP	5875	5	2550	3	1500	395.01	11850.30
GFRP	21150	18	7650	9	1750	1569.08	28243.40
Aluminum	5875	5	2550	3	2700	711.02	1279.83

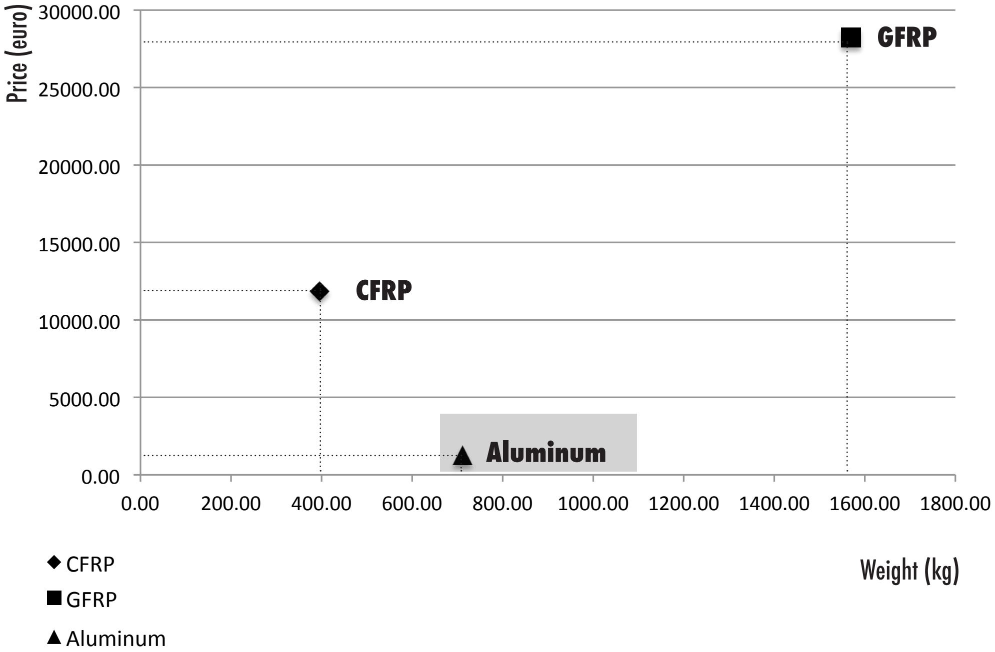


Figure 4.6 | Comparing graph of the three selected materials (price vs weight) for one DeMoLi21 truss

Materials	Thickness (mm)	Dencity (kg/m^3)	Weigth (kg)	Price (euro)
CFRP	2	1500	47.52	1425.6
GFRP	5	1750	138.6	2494.8
Aluminum	2	2700	85.536	153.9648

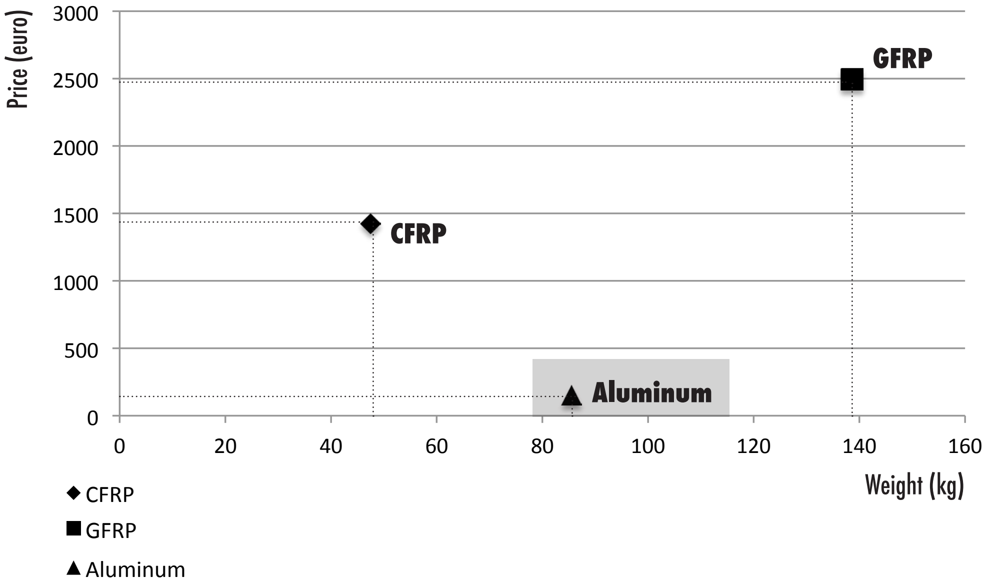


Figure 4.7 | Comparing graph of the two selected materials (price vs weight) for one deck panel

In general, Weight= Volume x Density
Thickness GFRP= 2.5 x Thickness of Aluminum, therefore $V_{GFRP}= 2.5x\ V_{alum}$
$W_{GFRP}= 1750 \times V_{GFRP}= 1750 \times 2.5 \times V_{alum}= 4375 \times V_{alum}$
$W_{alum}= 2700 \times V_{alum}$
Consequently, the final weight, as well as the cost of a GFRP solution is much higher.
Comparing aluminum with CFRP although is a more lightweight solution the price is 10 times up and therefore is rejected.

In cases that interested companies judge that an even more lightweight structure will be more efficient regardless the high price, then the material can be change by keeping the same overall concept and making some adjustments in the Detailed Phase.

4.5 Aluminum in DeMoLi Bridge

Understanding the unique characteristics of aluminum alloys and exploiting them in ways developed by other industries can produce light, durable and cost-effective bridges. [4.13]
Aluminum has in fact proved itself as a suitable material for load bearing structures for more than one hundred years. It is not widely used in the bridge market (it is limited in military applications[12]), partly through ignorance, partly through misconceptions, but largely because designers have never been taught how to use it.

Why should we consider aluminum?
Aluminum is not some kind of funny steel. It is a material that has unique properties that need to be exploited and worked with. When used correctly, the results are light and durable structures that are cost-effective. It is also famous because of the wide variety of structural forms and shapes that can be created. These properties have been widely exploited in aerospace, railway carriage and architectural applications; they are also useful for bridgeworks.
With only a third of the density of steel, the strength-to-weight advantage of aluminum is significant. The low self-weight can be extremely useful for handling during fabrication, construction, transport and erection stages as well as in the final design of the completed structure and its supports. Low self-weight is especially relevant for moving structures.
The durability of aluminum alloys is extremely good, which is one of the most underestimated virtues of the material. A significant reason for using aluminum is its excellent corrosion resistance, which is attributable to the naturally formed from exposure air protective oxide film. This film is usually invisible, relatively inert and adheres strongly to the metal surface. Once formed, it prevents further oxidation and reforms naturally if damaged. Under most atmospheric conditions, no coating is necessary. [4.13]
As it was analyzed before, it competes with CFRP in mechanical properties but with much lower cost. Price per tone for the basic material is high compared with steel (much lower than FRP), but when fabrication, erection and treatment costs are taken into account, there is little difference for the completed structure. Aluminum will often be cheaper than steel or concrete when whole-life costs are calculated.
Moreover, aluminum can be formed or extruded into simple, complex or bespoke shapes that allow for structural efficiency, as well as ease of fabrication. Custom Sections are really common. Ninety percent of all sections produced by aluminum extruders are individually designed and therefore, they are only available for the

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[12] Aluminum is particularly suitable for military bridges, where the need for portability and speed of erection favors materials with a high strength-to-weight ratio. The majority of military bridges built since 1960 have been built from aluminum.

use by the designer/purchaser of the section. This explains the special stock situation, which applies to aluminum sections and why standard sections don’t exist. [4.12]

Last but not least, aluminum is a material of excellent recyclability. The weight losses when remelted and also the degrading of quality in the recycling process are very low. All this will lead one day to a reduction of the exploitation of bauxite, though the quantity of aluminum in use will increase. Many people complain about the high consumption of energy needed to produce a kg of aluminum. However, taking into account the very small quantity of energy needed for remelting aluminum, its often cited disadvantages are eliminated. [4.12]

In general, the term *‘aluminum*’ is used, although in reality the structural materials of interest are all alloys of aluminum with small percentages of other elements added. [4.13] There are many different aluminum alloys available, and each of these in different tempers or heat treatments, such that the combinations run into hundreds. In total, there are eight basic “families” of alloys available. For the bridge engineer, however, there are only three families that need to be considered, and a relatively small number of alloys and tempers within each family. These are the series 5xxx, 6xxx and 7xxx, which they will be further analyzed. These are all alloys that are readily available, have good corrosion and strength characteristics and are easily fabricated.

There are also different types of allows according to their form. These are the extruded- wrought alloys and the casted- casting alloys, which are analyzed below.

4.5.1 Designation of Wrought Alloys

Aluminum alloys are categorized by the main alloying element and an internationally recognized four-digit reference is used. The alloys that are of interest to the bridge engineer are the following[13]:

- 5xxx series alloys have magnesium as the main alloying element. These alloys have the best corrosion resistance but are rejected for the proposal design because they are ideal for sheet and plates products and extrusions are only available in non-heat-treatable form[14].

- 6xxx series alloys have magnesium and silicon added as the main alloying elements. The 6xxx series alloys are readily extrudable as well as being available in sheet and plate form. These alloys are the most commonly used in structural and architectural applications, principally on account of the forms and shapes that can be created by extrusion. The alloys are available in a range of tempers (indicated by the letter T followed by a number, e.g. 6061, T4). They are readily weldable and give good all-round performance.

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[13] For the experienced engineer the choice of alloy and temper is not very difficult, especially after the clarification of the following points:
Which level of strength is needed?
Is high welding strength really necessary? (Or: Is it possible to avoid welding at distinct locations, e.g. may depend on size of sheet available)
Which form of semi-product is needed: sheet/plate/extrusions?
What are the quantities needed – are they available from stock?
Are individually designed sections of quantities sufficient for production?
Are filigreed/multi-hollow sections of advantage or needed?
Is there a need for high ductility material?
Is bendability/formability of sections needed?
Is foldability/formability for sheet material required?
Is decorative anodisability necessary?
Is exceptionally good corrosion behavior required (for special applications)?
Are there special requirements with respect to elevated temperatures?
Last but not least, what will be the materials cost? There are considerable differences between the various alloys and the semi products and often the engineer is forced to change the design to make cost compromises.

[14] EN AW-5083 and EN AW-5754 are the common alloys for the design of conventional structures from sheet. Extrusions in these alloys are standardized but scarcely on the market. The high hot forming resistance of these alloys allows only simple sections with greater wall thicknesses and no hollow sections using port-hole dies. But seamless tubes are possible and available on the market.
EN AW-5049, -5052, -5454 and EN AW-6005A are not very frequently used for structural works. Their use is confined to special applications and products/manufacturers.

- 7xxx series alloys have zinc and magnesium as their main alloying elements[15]. The 7xxx alloys are stronger (having inferior corrosion resistance) than the 5xxx and 6xxx alloys, and have their strength increased by heat treatment. They are harder to form and are more expensive than other common alloys and therefore are also rejected.

The 1xxx and 3xxx series are not heat-treatable and fairly low pressure. The 4xxx series is good for non structural casting. Alloys that belong to category 8xxx are not suitable for bridge applications since they are typically allow for structural sheeting[16].

Consequently, in the proposal design the selected materials belong to 6xxx series. EN AW-6082 and AW-6061 are the classic alloys corresponding in their proof stress to normal mild steel and therefore preferred by engineers for structures resembling conventional steel work. EN AW-6061 contains more copper; this may influence the appearance and the weldability, depending on the actual copper content of a batch. [4.12]

Important for designers are the values for EN AW-6060/6063. These are the most common extrusion alloys because they are very cost effective. They allow the production of filigree and very complex extruded sections at moderate cost, since high extrusion speeds and air quenching are typical in production. The characteristic value of the proof strength, 140 - 160 N/mm², seems to be low, but under most design conditions they are sufficient for structures. [4.12]

EN AW-6106 also belongs to this type of alloy but has better welding strength.

Finally, EN AW-6005 combines strength with good extrudability and this is the reason why this alloy is in very common use for railway carriages.

4.5.2 Designation of Casting Alloys

Cast and forged parts are always individually designed parts and ordered directly from the manufacturer.

For cast products quite different alloys are preferred. Casters prefer type 4xxxx alloys with high silicon content, since with these alloys good quality is easily produced[17]. Casting alloy designations have the prefix “EN AC-” to distinguish them from wrought alloys and have 5 digits in total. The first digit means the same as for wrought alloys; for instance, it defines the principal alloying element. The most frequently used alloys are EN AC-42100, -43300 and -44200 due to their good castability. The alloy EN AC-51000 (AlMg5) is difficult to cast and therefore it is used relatively seldom despite the fact that engineers like to make use of it due to its bright surface and anodisability (other alloys are more or less greyish, especially when anodised). [4.12]

4.5.3 Aluminum Bridge Decks

Several manufacturers have developed large multi-voided hollow extrusions specifically for forming orthotropic bridge decks. The extrusions are typically formed from alloy 6061 in the T6 condition. The weight of these deck systems is between

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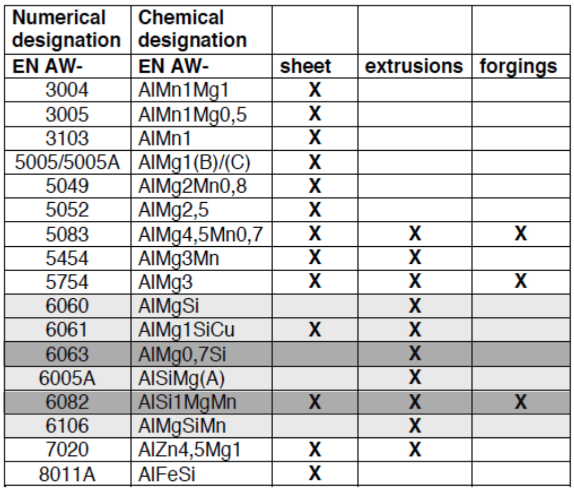
[15] EN AW-7020 is standardized for sheet and extrusions. It has the highest strength values of the alloys listed in EN 1999-1-1. Since the necessary quenching rate is low, the alloy shows better strength after welding by natural hardening. Semi products from this alloy are relatively higher priced. The alloy is often used for military bridges and also for cranes and cherry pickers. Depending on the application a second artificial hardening process is recommended after welding.

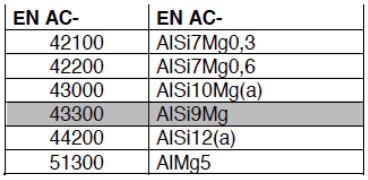
[16] The alloys EN AW-3004, -3005, -3103, -5005 and -8011 are typical alloys for structural sheeting. They are used with low thicknesses and as roll formed products used for roofing and cladding. Often alloys of this group are also used for special façades (anodised, organic coatings). If adopted normally greater quantities of material are needed and the decision as to the best and most economic alloy should be made together with the manufacturer.

[17] There is however a difference concerning casting alloys with magnesium and silicon additions made to develop hardening effects and hence higher mechanical properties, through controlled precipitation of the magnesium silicide phase. In casting alloys higher levels of silicon are of benefit in reducing the tendency to shrinkage cracking. Therefore, even in the magnesium silicide phase hardening casting alloys, silicon is well in excess of other elements. The logic of the designation system therefore requires that these alloys have a “4” as first digit in contrast to the magnesium silicide hardening wrought alloys which have a “6” as first digit.[4.12]



Numerical designation EN AW-	Chemical designation EN AW-	sheet	extrusions	forgings
3004	AlMn1Mg1	X		
3005	AlMn1Mg0,5	X		
3103	AlMn1	X		
5005/5005A	AlMg1(B)/(C)	X		
5049	AlMg2Mn0,8	X		
5052	AlMg2,5	X		
5083	AlMg4,5Mn0,7	X	X	X
5454	AlMg3Mn	X	X	
5754	AlMg3	X	X	X
6060	AlMgSi		X	
6061	AlMg1SiCu	X	X	
6063	AlMg0,7Si		X	
6005A	AlSiMg(A)		X	
6082	AlSi1MgMn	X	X	X
6106	AlMgSiMn		X	
7020	AlZn4,5Mg1	X	X	
8011A	AlFeSi	X		

Wrought alloys listed in EN 1999-1 and the form of standardized semi products (table 3.2 1-c)



EN AC-	EN AC-
42100	AlSi7Mg0,3
42200	AlSi7Mg0,6
43000	AlSi10Mg(a)
43300	AlSi9Mg
44200	AlSi12(a)
51300	AlMg5

Casting alloys listed in EN 1999-1 (table 3.3)

Figure 4.8 | Aluminum Alloys listed in EN 199-1 [4.7]

	Minum Strengths (Mpa)			
	Normal State		Heat Affected Zone (HAZ)	
Alloy- Temper	Yield Strength (fo)	Ultimate (Tensile) Strength (fu)	Yield Strength (fo, HAZ)	Ultimate (Tensile) Strength (fu, HAZ)
6005A, T61	200	250	115	165
6060, T6	140	170	60	100
6061, T6	240	260	115	175
6063, T6	160	195	65	110
6082, T6	250	290	125	185
6106, T6	200	250	95	160

Figure 4.9 | Strength properties for common extruded alloys [4.7]

Material	Compnents	Production Method	0.2% Proof Strength- Yield Strength (fo) (Mpa)	Ultimate (Tensile) Strength (fu) (MPa)	Allowable Strength (Mpa) - material factor 1.25
EN-AC-43300	Hinged Connections	Casting	147	203	118
EN-AW- 6082, T6	Leaves	Extrusion	250	290	200
EN-AW- 6061, T6	Deck Panels	Extrusion	160	195	128

Figure 4.10 | The applied materials in DeMoLi Bridge with their associated mechanical properties

50 and 70 kg/m^2 (in DeMoLi design this is 60kg/m^2 including the sided longitudinal beams), which is only about one-tenth that of a typical concrete deck. The aluminum decks have good corrosion resistance, which makes them ideal for temporary applications.

According to the above, the selected aluminum alloys for each element of the DeMoLi Bridge with their mechanical properties are show in Figure 4.10. The selection is based on their mechanical properties and their usability in foundry industry.
Although the strength of the parts that welds are situated, has to be compared with the ultimate tensile strength of the heat affected zone, for simplicity reasons during the checks the strength of all the elements is taken as the 0.2% proof stress of the parent material. Material factors are specified in the Eurocodes, by which the material strength values must be divided. The factors are equal to 1.1 for parent material and 1.25 for the heat-affected zones (HAZ). Since the normal 0.2% proof strength is used instead of the reduced strength to the HAZ the maximum material factor of 1.25 is applied.

4.6 Diana Structural Analysis

After the geometry finalization and the material selection, a linear structural static analysis in Diana software is carried out to evaluate the position of maximum stresses and deflections occurrence under the four load cases for both one truss and one deck panel.

The checks comprise:

A. Check of the stresses and

B. Evaluation of Deflections

To approve the design regarding to the requirements of safety, serviceability and durability, a reliability approach is adopted. Reliability is set by a limit state[18] design principles of recognized structural regulations. The process of reliability approval aims to the evaluation of the structural behavior of the generated model, in order to verify that calculated effects do not exceed the values of allowable strength and deformation limits (acceptable values of displacements) according to the ultimate limit states. The basic design condition of this method can be written in the form [4.14]:

$\sigma max<\sigma per,$

with $\sigma per=\sigma crit/k$

where,

σmax is the maximum equivalent stress (Von Mises) according to the Diana calculations and the coefficient k (greater than 1) is the explicit measure supposed to take into account all types of uncertainties. According the selected materials and the Eurocodes, k, in proposal design, is calculated as 1.25.

Concerning the deflections, according to TDTC: *Deflections are not limited directly but must be considered when they cause changes in loading, affect fit of alignment, or affect the use of equipment*. Generally, it is related to the feeling and the comfort of the users.

The deflection criterion is usually represented by a deflection index, L /xxx , where L is the span length and ‘‘xxx ’’ is a value to be specified to satisfy the stiffness requirement for a specific design.

4.6.1 Truss

The truss structure has to be stable and despite its folding capability, when it is fully deployed, it has to be able to carry its own weight and the live loads to which it will be subjected (pedestrians, vehicle, etc.). Therefore, under normal circumstances, it should have adequate margins and stiffness in all structural elements and in their interconnections for all the different spans, from 6-21m.

Testing is done for all the possible length of one truss, from DeMoLi6 to 21. However, the focus is on the biggest length of 21m (14 modules), where is the most critical one. Therefore, the structural analysis and calculations are focusing on this length and the DeMoLi21 truss in deployed configuration.

For the design of the truss model, several assumptions are done:

All members are perfectly straight,

All loads are applied as point loads at the nodes and

All joints are pinned and frictionless.

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[18] According to EN 1990- 1.5.2.12, Limit States are states beyond which the structure no longer fulfills the relevant design criteria.

The term “failure” in bridge design is usually taken in a more restricted sense, which maybe defined as the onset of unacceptable deflections. Failure is generally a consequence not only of the geometry of the structure but also of the nature of the material of which is composed.

It is divided into:

a. The occurrence of excessive or uncomfortable- undesirable deflections under service loads that doesn’t involve collapse of the primary structure and

b. The incipient collapse of the structure where the bridge falls to the ground.

The second type of failure means that the bridge, when viewed after the event, is no longer interact; but it begins with the development of excessive deflections that accelerate with time. In modern terminology the first is grouped with other serviceability limit states; the second is regarded a ultimate limit state. [4.9]

DeMoLi21- N14, nodes= 15

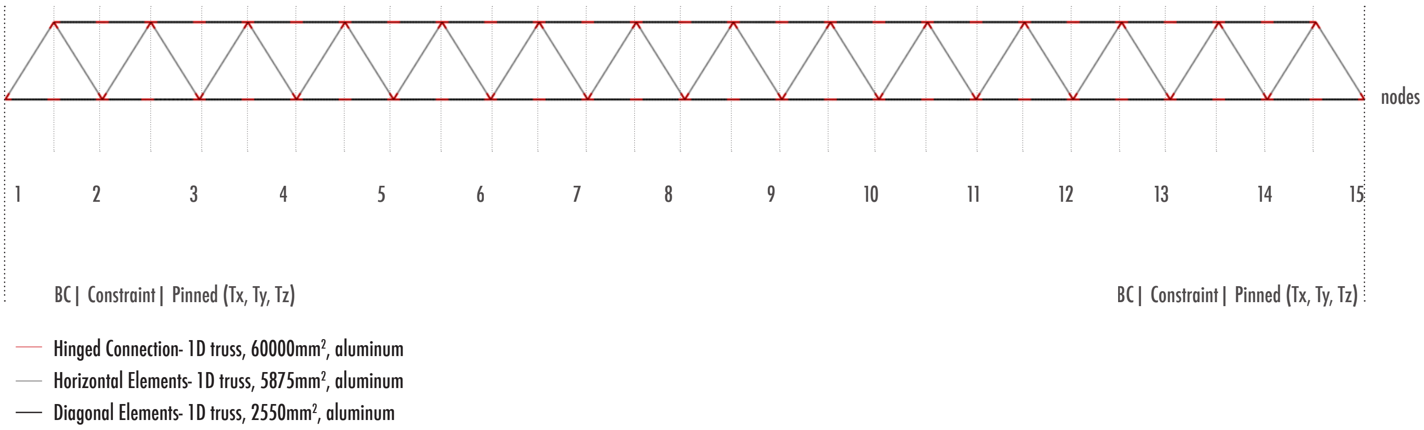
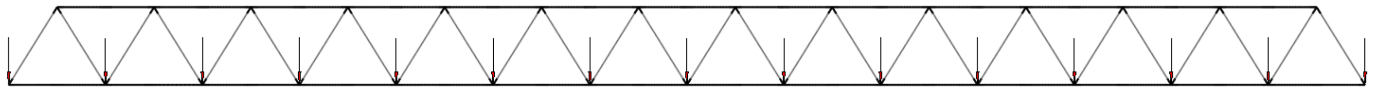


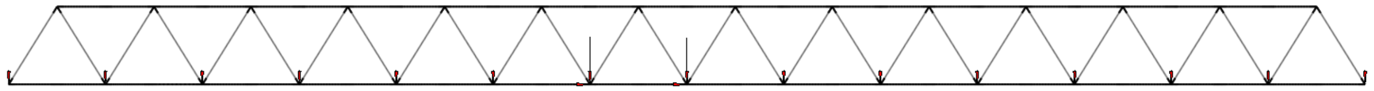
Figure 4.11 | Complete model of one truss with all the structural elements and the boundary conditions

Loads per Nodes (N)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LC1- pedestrians	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136	19136
LC2- LM1	2336	2336	2336	2336	2336	2336	114836	114836	2336	2336	2336	2336	2336	2336	2336
LC3- HS20-44	2336	2336	2336	33041	2336	2336	125070	2336	2336	2336	125070	2336	2336	2336	2336
LC4- MLC30	2336	2336	2336	2336	2336	2336	36453	36453	36453	2336	2336	2336	2336	2336	2336

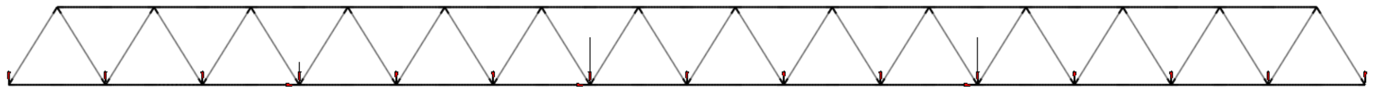
LC1: Pedestrians- 5kPa



LC2: Vehicle, LM1- according to EN1991-2



LC3: Truck, HS20-44 loading- according to American AASHTO



LC4: Tracked Vehicle, MLC40- according to TDTC

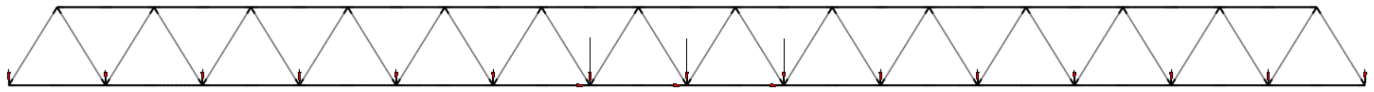
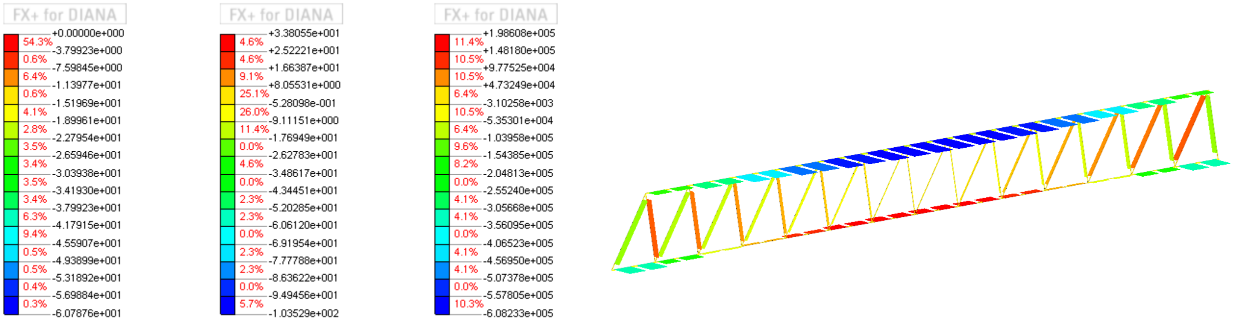


Figure 4.12 | The four load cases of DeMoLi21 truss. The red arrows indicate the loads to the nodes

LC1: Pedestrians- 5kPa

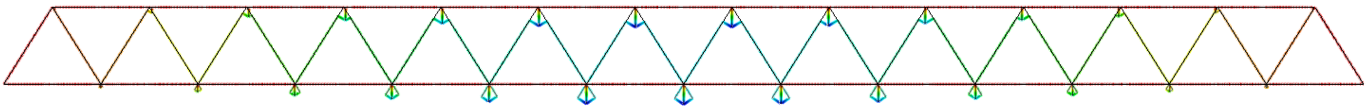


Displacement (Dtz) (mm)

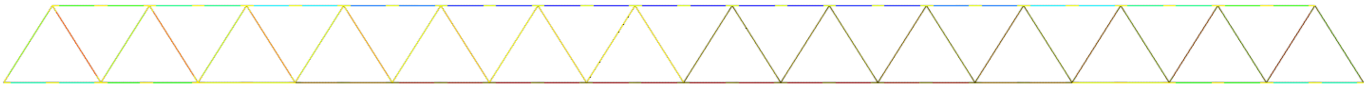
Stresses (Sxx) (N/mm^2)

Axial Forces (Nxx) (N)

Displacement (mm) d_{max} = 60mm



Stresses (N/mm^2) $s_{max} = -103N/mm^2$



Axial Forces (N) N_{max} = -6.08e05N

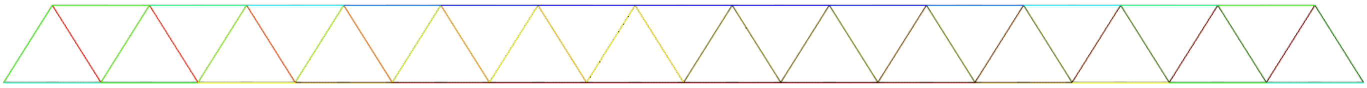
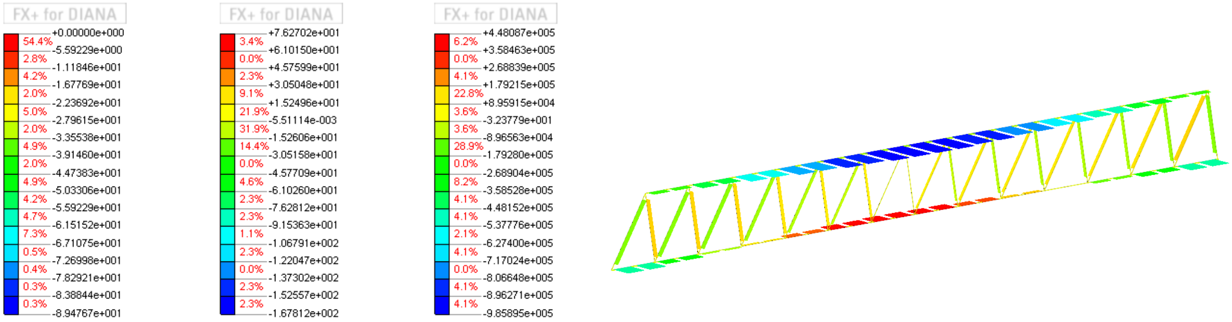


Figure 4.13 | Results from Load Case 1

LC2: Vehicle, LM1- according to EN1991-2

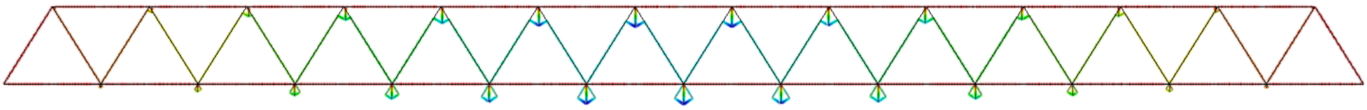


Displacement (Dtz) (mm)

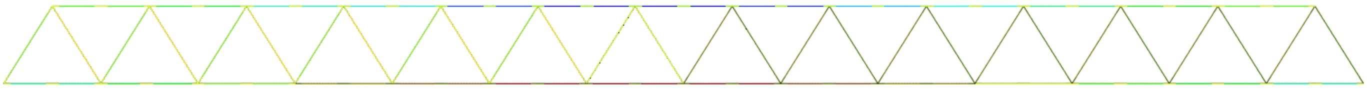
Stresses (Sxx) (N/mm^2)

Axial Forces (Nxx) (N)

Displacement (mm) d_{max} = 89mm



Stresses (N/mm^2) $s_{max} = -167N/mm^2$



Axial Forces (N) N_{max} = -9.85e05N

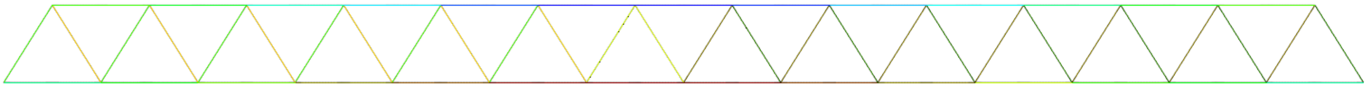
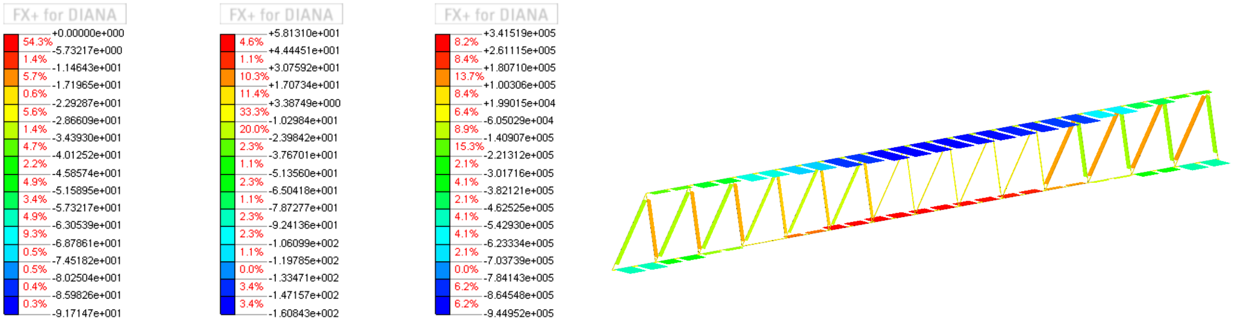


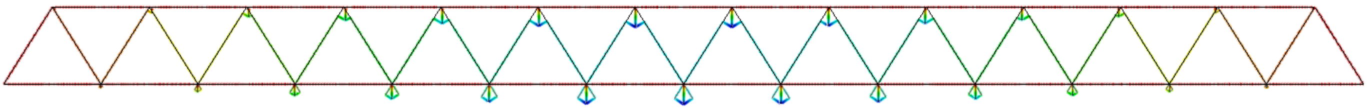
Figure 4.14 | Results from Load Case 2

LC3: Truck, HS20-44 loading- according to American AASHTO

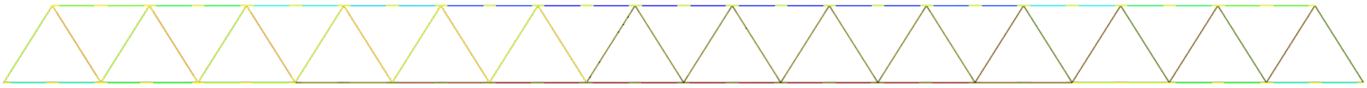
Displacement (Dtz) (mm)   Stresses (Sxx) (N/mm^2)   Axial Forces (Nxx) (N)



Displacement (mm) d_{max} = 92mm



Stresses (N/mm^2) s_{max} = -160N/mm^2



Axial Forces (N) N_{max} = -9.44e05N

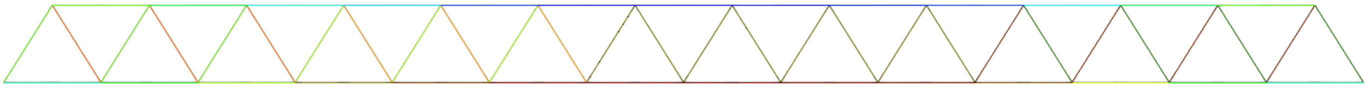
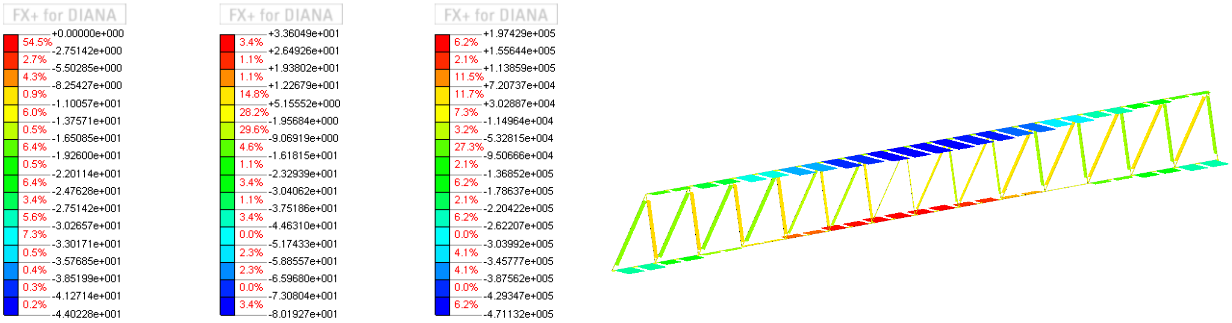


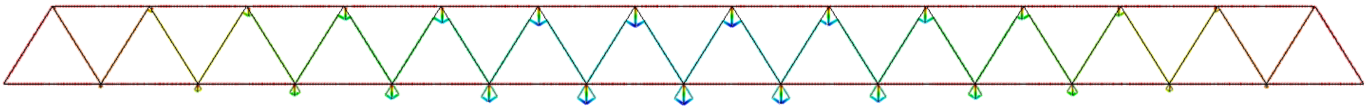
Figure 4.15 | Results from Load Case 3

LC4: Tracked Vehicle, MLC40- according to TDTC

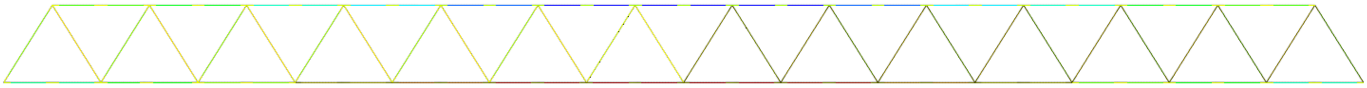
Displacement (Dtz) (mm)   Stresses (Sxx) (N/mm^2)   Axial Forces (Nxx) (N)



Displacement (mm) d_{max} = 44mm



Stresses (N/mm^2) s_{max} = -80N/mm^2



Axial Forces (N) N_{max} = -4.71e05N

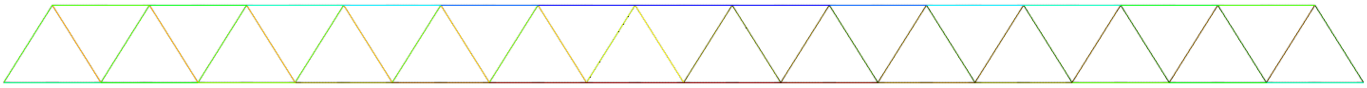


Figure 4.16 | Results from Load Case 4

The truss is shaped in a more rational shape. The general dimensions (width, span, height) are kept the same, whereas the truss is illustrated as a simple Warren Truss made of one-dimensional truss elements [Figure 4.11]. The loads are applied on the deck surface, they are transported to the nodes of the truss and finally they are transmitted by the diagonal members to the horizontal members and back to the bearings.

The four load cases and their magnitude of each load are visualized in Figure 4.12. Since the structure is split due to its symmetrical geometry, the calculated dead loads for all the load cases are the one truss and the weight from the half deck's width. For LC1, the uniformly loads from pedestrians of 5kPa is distributed to the nodes. For the rest vehicle cases, only one wheel per axle is considered and as it was clarified in Planning and Problem Definition Phase only one vehicle is presented on the bridge in any load case. The position of the applied loads is in the middle of the truss since this is the most critical area.

The support points are defined as pinned to the both end sides of the truss. Through this, the foundation can resist any net force in the plane of the truss.

Results

A. Stresses and Axial Forces

The bridge is safe as long as the resisting forces are bigger than the applied forces. The design of truss structures eliminates torsion and shear forces, presenting only two stresses; pure compression and tension[19]. As the truss bridge is loaded, the top chord is compressed and the bottom surface is stretched or put in tension. In general, the upper chord is subjected to larger internal axial forces in compression and negative stresses, in comparison with the other members as shown in the diagrams [Figure 4.13-16]. However, due to the modular character of the bridge, the sections are kept the same. Forces on the diagonals have much lower values compared with the horizontal members, which alternate between compression and tension (approaching the center), while elements near the center must support both tension and compression in response to live loads.

The stress levels in the middle top chord of the truss are the maximum ones in all cases. The stresses are negative and result from the maximum compression axial forces. Comparing the four load cases, the most severe case regarding the stresses is the LC2. The highest calculated stress in this case is 167N/mm^2, occurring in the horizontal elements of the upper chord. This value has sufficient margin compared with the allowable stress for the material, which is equal to 200MPa (N/mm^2).

Since, the hinged connections are made of a different material with a lower allowable stress and therefore are checked separately. There maximum value is raised at76N/mm^2, which is smaller than the allowable one (=135MPa) fulfilling the relation of σmax<σper.

Finally, the values of the axial forces are evaluated in Detailed Design Phase for calculations relevant to the hinged connections and the finalization of the cross section of all the trussed elements.

B. Deflection

Although, in a normal bridge system there is an unwritten rule that the overall maximum deflection has to be less than 1/300 of the total span, the military bridge design code GJB 1162-91 recommends that the maximum deflection could be less than L/150. The maximum deflection for the DeMoLi21, according to L/300 is equal to 70mm, whereas the L/150 is 140mm. According to the purposes of DeMoLi bridge the following assumption is done: In LC1, and the uniformly distributed load of pedestrian the maximum allowable deflection is L/300= 70mm, while in cases of vehicles this is reduced to L/150= 140mm.

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19. Compression: A 'squashing' force, this force acts to shorten each member it's acting upon.
Tension: A 'pulling' force, this forces acts to lengthen each member it's acting upon.

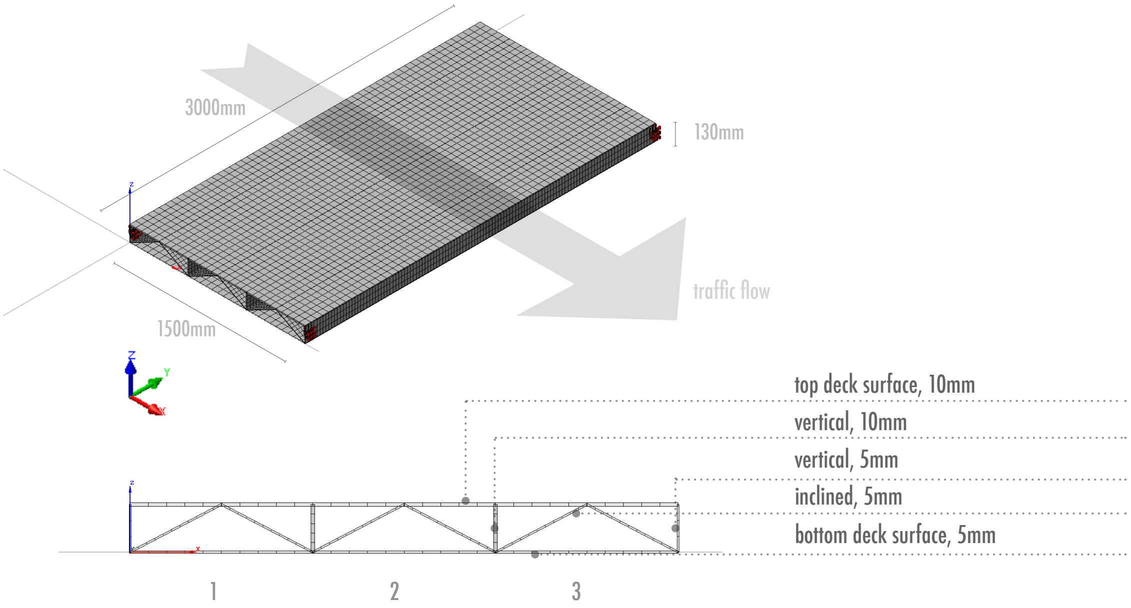
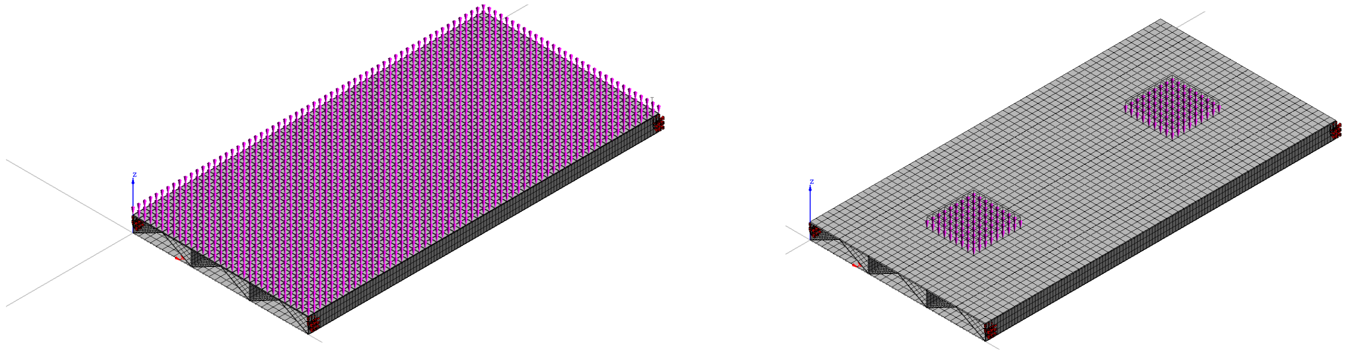


Figure 4.17 | Complete model of one deck panel with all the structural elements and the boundary conditions (3D meshing and cross section)

LC1: Pedestrians- 5kPa

LC2: LM1- according to EN 1991-2



LC3: Truck, HS20-44 loading- according to ASHTO

LC4: Tracked Vehicle, MLC40- according to TDTC

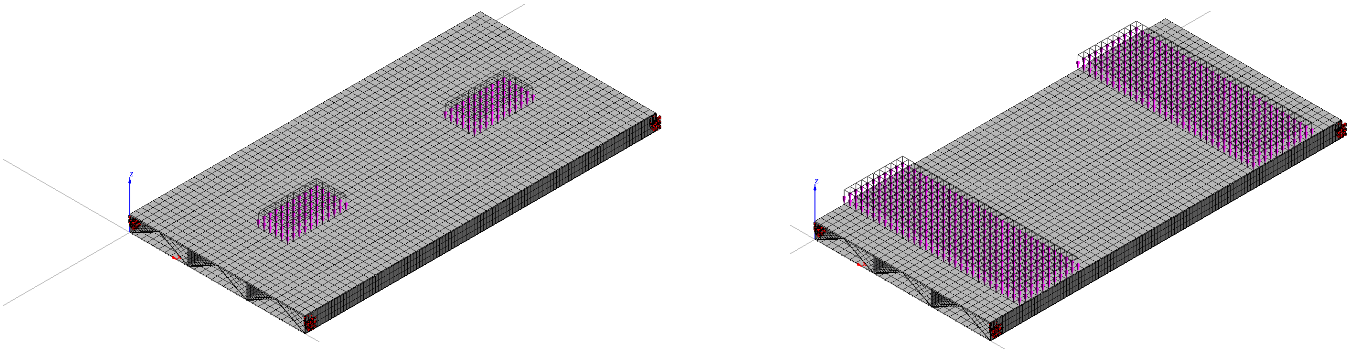


Figure 4.18 | The four load cases of one deck panel. The purple arrows indicate the loads

The maximum deflections for the load cases from 1 to 4 are 60mm (L/350), 89mm (L/235), 91mm (L/230) and 44mm (L/477), respectively. All of them are considering as acceptable values satisfy the admissible deflection limit.
The diagrams in Figures 4.13-16 show the stresses, deflection and axial forces for the four load cases with their maximum values.

4.6.2 Deck Panel

The developed model is illustrated as a multi-voided structure. These voids arise from the hollow extrusions that are used to construct the deck. The model consists of three extrusions, each measuring 500mm (width) x 3000mm (length) x 130mm (height) and it has two horizontal, two vertical and one inclined plates, which slant downwards. These extrusions create one panel of the bridge deck with general dimensions of 1500mm width, 3000mm length and 130mm height. The deck section is formed by welding the extrusions together. Although the real structure is made of three parts, for the modeling purposes the panel is illustrated as a one element. By default, for the modeling of such a bridge deck, the thin plate is simulated as flat shell elements with specify thickness. The thickness of the upper flange is 10mm and 5mm for all the other members. Where the extrusion sections are welded and the real thickness is doubled also the calculated is doubled and is equaled to 10mm. The longitudinal beams along of the deck section, as they will be explained later in the next phase, are not modeled for simplicity reasons. The traffic flow is perpendicular to the extrusion profiles. An illustration of the geometry with the applied properties is shown in Figures 4.17. The deck is loaded out-of-plane by uniform distributed loads of pedestrians and vehicles as well as the weight of the deck. Finally, the deck is pinned to the four edges of the rectangular panel. Due to the fact that in reality the panel is not point-supported, more than one point are set as its supports.

Results

A. Stresses

It is noticed that in all cases high peak stresses occur at the supports points. This is due to the node constraints applied to the Finite Element Model. In reality the supports are not point constraints, but cover a certain area. In such a case, the peak stresses flow because the actual supporting way will eliminate the presented stresses at these points.

The maximum stresses (with percentage more than 0.3%) are displayed in LC3 and they are equal to 119N/mm^2. Consequently, the unity check (119/123) is equal to 0.92, smaller than 1.0. The results indicate that both the strength and stiffness satisfy the design requirements.

B. Deflection

According to the AASHTO LRFD Bridge Design Specification, the allowable deflection of the bridge deck in service limit state is equal to L/800. The span of the bridge deck is 3000mm, so the maximum displacement according to the specifications is equal to 3.75mm. This value is considered in LC1, while in the rest cases, with the applied loads of vehicles, the values of displacement are not further tested given that the allowable stresses are fulfilled.

LC1: Pedestrians- 5kPa

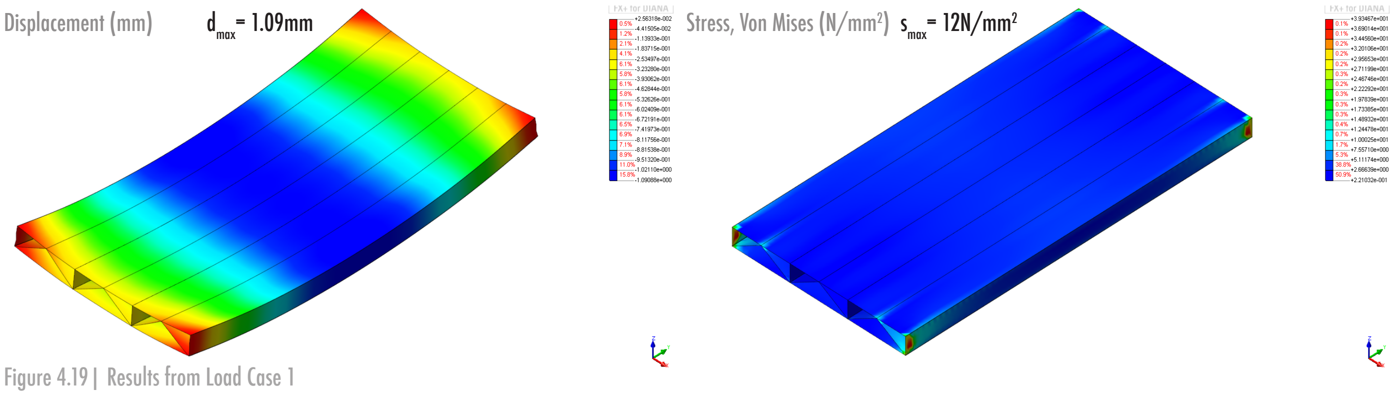


Figure 4.19 | Results from Load Case 1

LC2: LM1- according to EN 1991-2

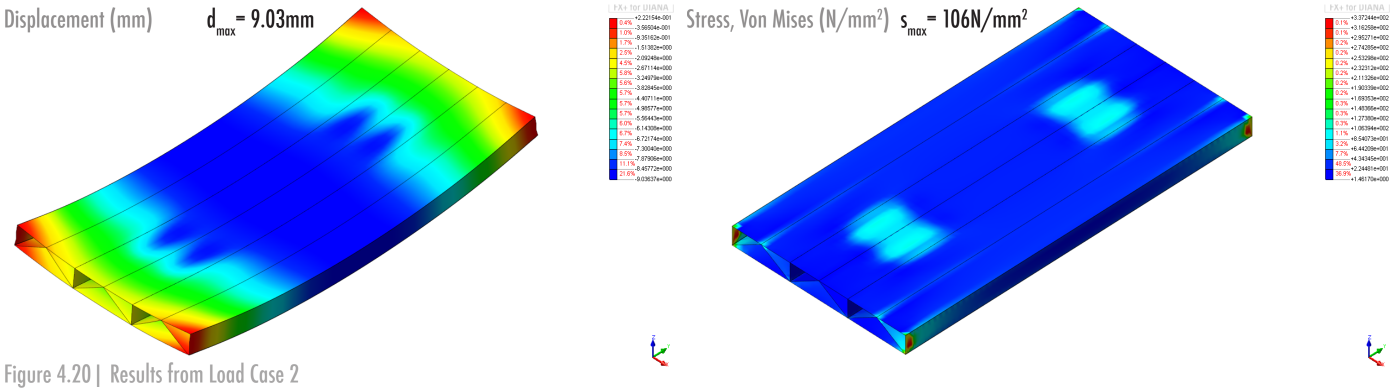


Figure 4.20 | Results from Load Case 2

LC3: Truck, HS20-44 loading- according to ASHTO

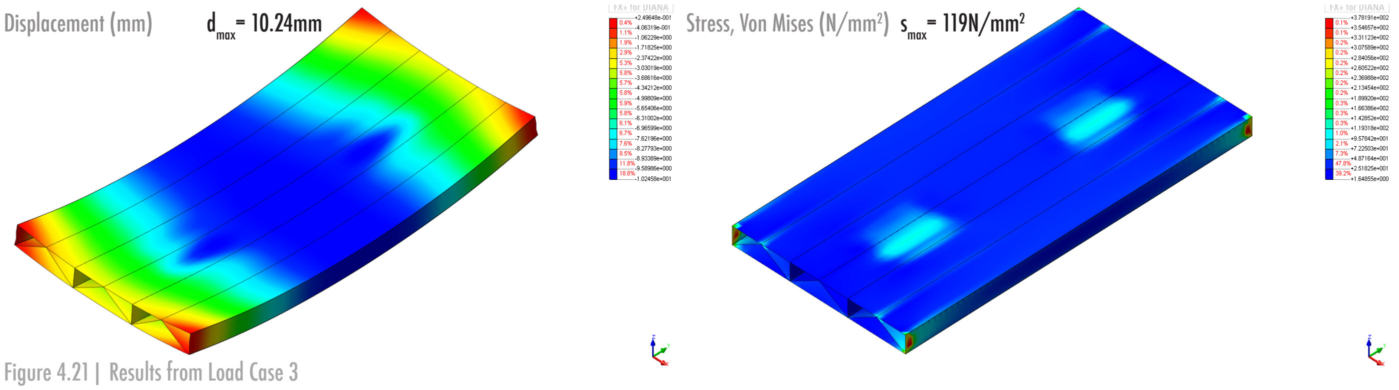


Figure 4.21 | Results from Load Case 3

LC4: Tracked Vehicle, MLC40- according to TDTC

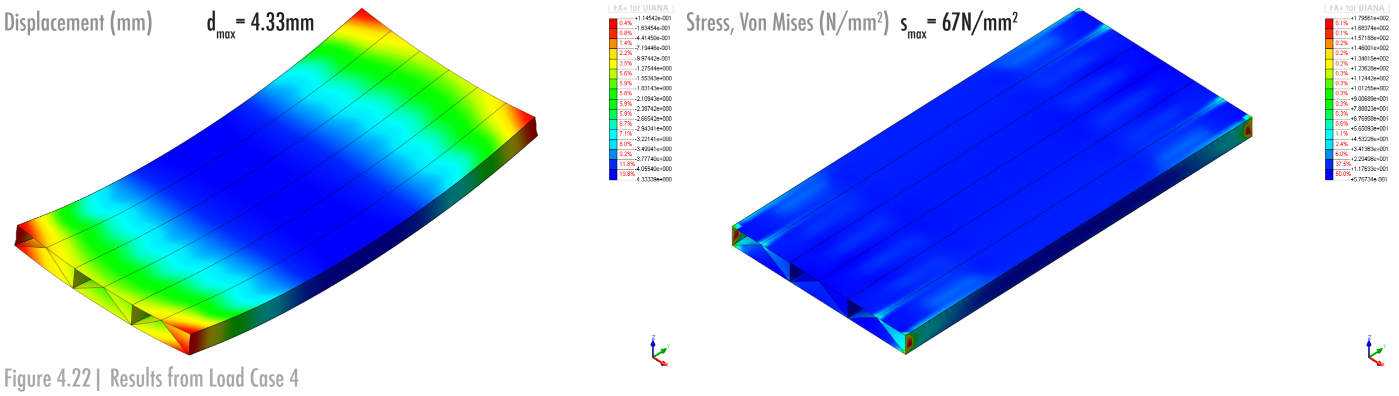


Figure 4.22 | Results from Load Case 4

5.

Detailed Design

Detailed Design or Developed Design Phase, is the process of taking on and developing the approved concept design, transforming it into final cross-disciplinary design. It provides the links for integrating all the conceptual and preliminary data into a complete, finished digital product.
By the end of Detailed Design process, the proposal solution is dimensionally correct and co-ordinated, providing a detailed specification for each component, thoroughly describing their interfaces and their functions.
DeMoLi solution is divided into the folding truss, the bridge deck and some extra elements like bearings and access ramp. All of structural and non-structural components of these are studied and visualized deeply during the Detailed Desigb Phase, which serves the basis for the Implementation.

5.1 General Detailing View

There is a well-known aphorism *'the devil is in the detail'*. [5.1] Consequently, one the major challenge for the design of the DeMoLi emergency Bridge is related to an effective detailing of the whole structure. The Detailed Phase becomes crucial because can influence the integrity, the weight and the overall efficiency of the entire structure.

The bridge is composed of the decking system (part 5.3) supported by two pairs of folding trussed beams (part 5.2), as it is shown in Figure 5.1. These two elements are the primary interested of detailing phase. Moreover, there are some extra elements like the access ramp and the bearings that are analyzed (parts 5.4 and 5.5).

The concept of DeMoLi Bridge is based on several key principles, which are applied also in the detailing design. These are:

Modularity: Both truss superstructure and decking system are made of independent, identical parts, which are proper assembled in order to act as an integral whole, following the modular concept. According to modular design, the elements have to be independence and exchangeability at the same time. The connections between the independence components are the exchangeable elements of the object, which contribute to the increased demountability and transformability of the structure. As a result, during the design process, emphasis is given in members- as the independent elements- and their connections- as the exchangeable ones.

Standardization Simplicity: All the components are standard in production with as less variety as possible. Thus, the manufacturing and assembly processes can easily be automated, reducing the overall cost.

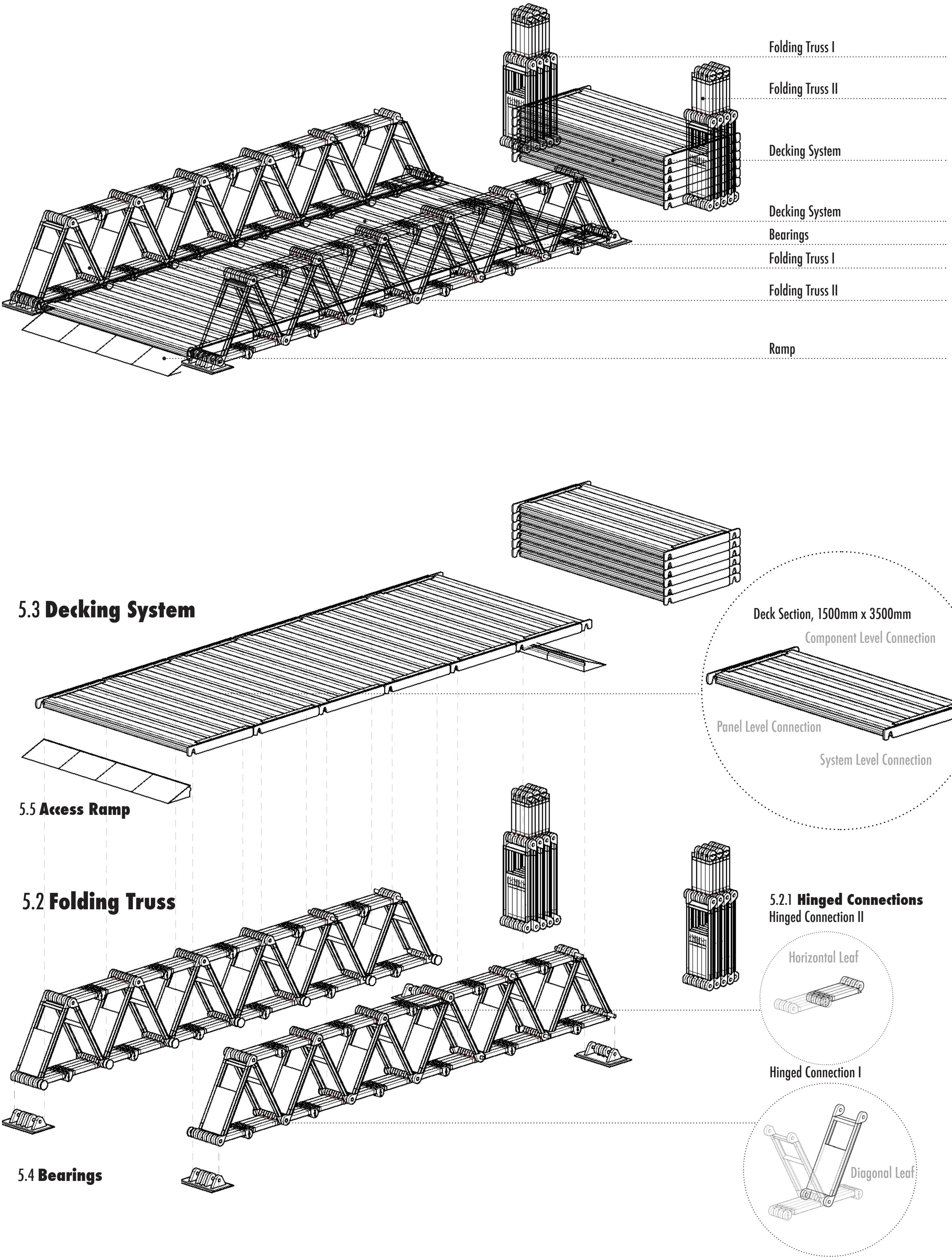


Figure 5.1 | 3D representation of DeMoLi9 Bridge's System

Stability: Another primary issue is the stability of the bridge. Although it is made of small parts with movable connections, when it is installed, it should transmit the idea of strength and give an impression of security. For this reason, a locking mechanism for extra safety is invented.
Lightweight: The requirement to illustrate a structure as light as possible also falls into its detailing design.
Economy: The selection of the "right" details (geometries, production techniques, etc.) in combination with mass productivity reduce the overall cost making the proposal design a desirable solution for emergency.

Joining methods

Techniques for joining an aluminum bridge are firstly analyzed and then the selected ones are designed.
Generally, they are summarized as:
- *Welding,*
- *Adhesive bonding and*
- *Mechanical fasteners.*

Welding is defined as the joining of materials by the use of heat (fusion welding) or force- pressure (solid state welding) or combining heat and force, with or without a filler metal. The welding of aluminum is widely established and has been developed into an important method of joining. Advantages of welded connections are saving of work and material, absence of drilling, tight joints, and no crevice corrosion. By the extrusion technique groove preparation and backing can be integrated in the profile. Strength reduction in heat affected zones can be compensated by locally increasing the thickness. [5.8]
Adhesive bonding is more common in high-performance applications, such as in aerospace and automotive industry, and has many advantages over the other methods. For example, unlike welding, the parts that are bonded do not distort and have up to a 20% increase in stiffness. Adhesive bonding also has higher stiffness than mechanical fasteners or spot welding since it creates a continuous bond and therefore has a more uniform stress distribution, which leads to more uniform work and therefore higher fatigue strength. Some disadvantages of adhesive bonding include manufacturing difficulties as well as some performance difficulties. Other disadvantages include the environmental, health and safety concerns since most high-performance adhesive are toxic and require energy to cure. Its major drawback is related to its high-cost.
Finally, the *mechanical fasteners* encompass a range of processes that utilize a variety of fasteners including nuts and bolts, screws and rivets, or mechanical interlocks to assemble materials without heating or pressure. Mechanical fasteners can be used on site whereas the above two techniques are mainly applied is an in-shop method. Furthermore, it permits assembly and disassembly with simple and inexpensive tools and commonly skills.
The most realistic and realistic joining technique for the proposed application is a hybrid of welding and mechanical fastening. They are the two of the most widely used and well-established methods of joining. Specifically, welding is used within the module (for the construction of the different elements of the truss and the deck panels) while mechanical fasteners are applied between inter-module connections, as they have to detract from the inherent modular bridge system.
In the next parts, the joining methods within and between the different elements for both truss and deck are analyzed.

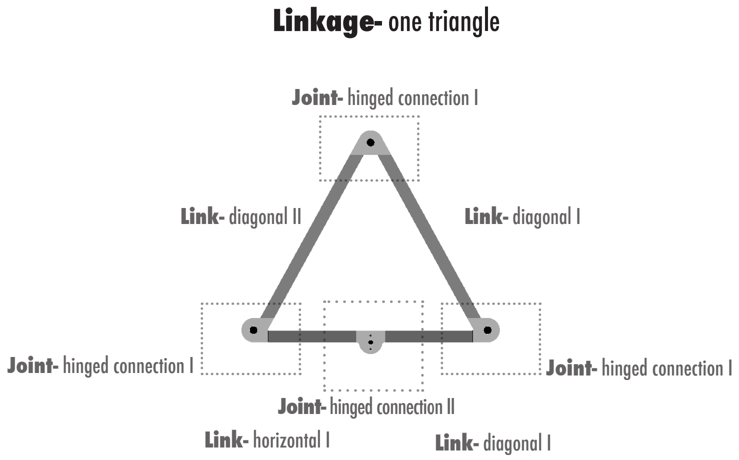


Figure 5.2| The structural composition of a bridge mechanism, scale 1:50

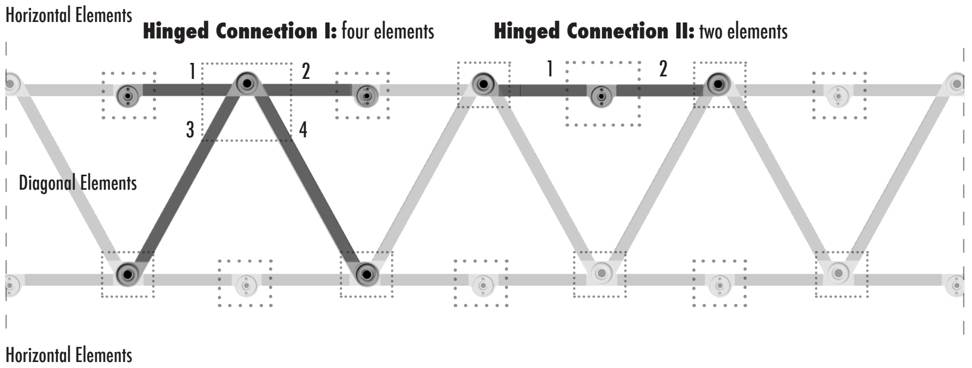


Figure 5.3| The hinged connections and the structural elements in DeMoLi Bridge, scale 1:50

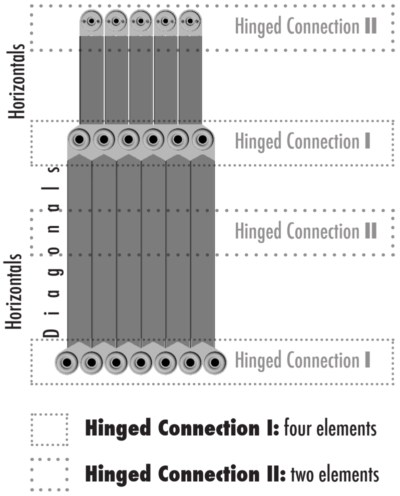


Figure 5.3| The structural composition of a mechanism and the relation to DeMoLi Bridge
Linkage= Triangle as a structural unit
Links= Leaves (horizontal & diagonal)
Joints= Hinged Connections I and II

5.2 Trussed Members

The current thesis, as an experimental project, deals with the design as well as the detailing of a new type of a deployable-collapsible truss for bridge applications, characterized by a network of multiple panels, which can be instantaneously deployed into a final self-supported and stable configuration, providing help in emergency.

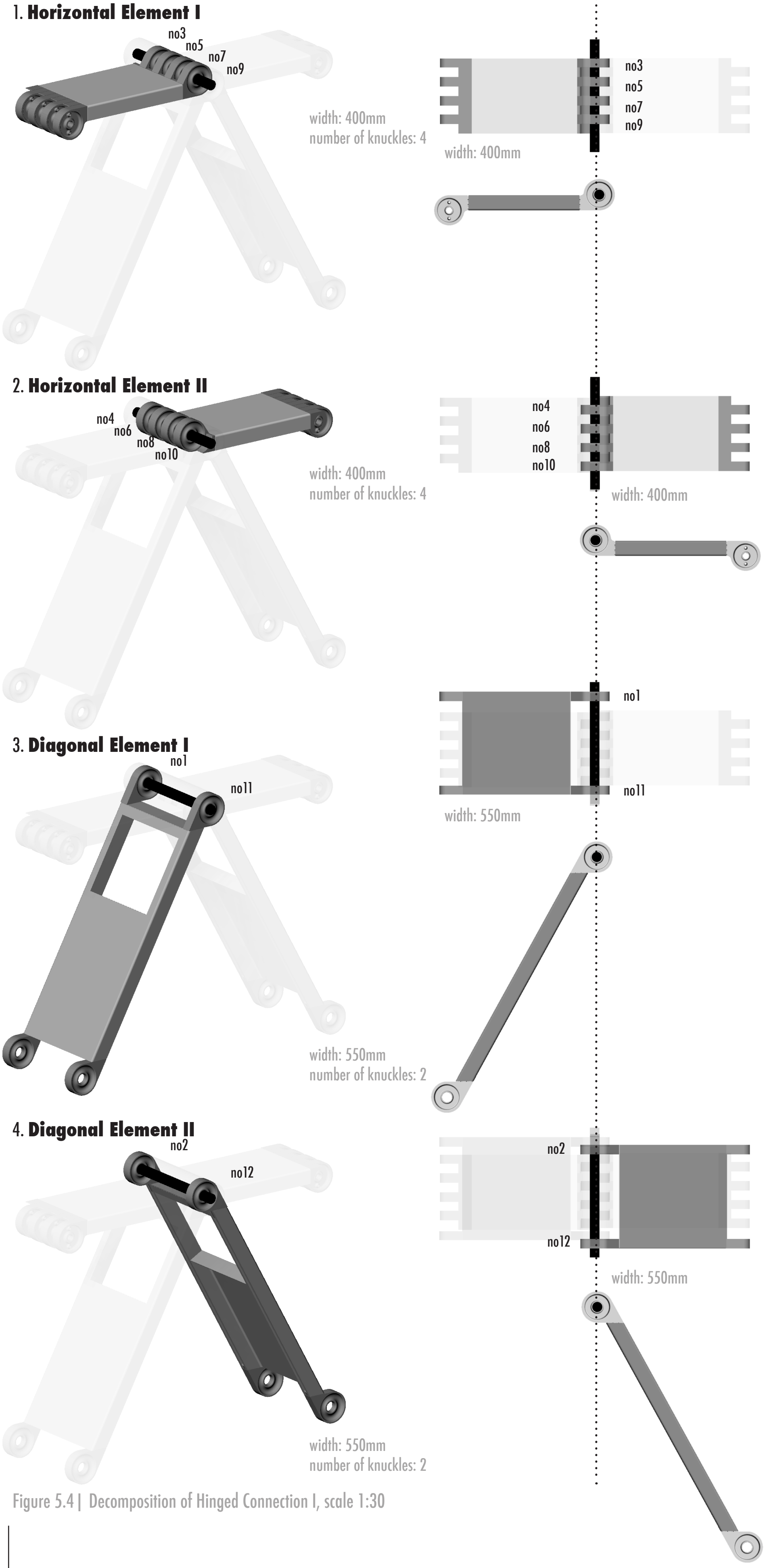
The keys to a successful concept of deployable structures is, first of all, to identify a robust building block (a general module), which is a simple deployable mechanisms; and secondly, to develop a way by which the building blocks can be connected to form a large deployable structure while retaining the ability to move freely.

In mechanical engineering field, a linkage is a particular type of mechanism consisted of a number of rigid, interconnected members, individually called links. The physical connection between two or more links is a movable joint. [5.10]

In DeMoLi design, linkage is each triangle of the truss. The four rigid members, which it is constructed, are the links, while the hinged connections located at the both edges of each link are the joints [Figure 5.2].

Inside each linkage, two different types of hinged nodes are formed. These are the *hinged connection I and II*. Their differentiations result from the number of elements that are connected and the position of their rotation axis. Hinged connection I is located at each corner of the initial triangle and connects four members (two diagonals and two horizontals), while hinged connection II, which connects two members and more specifically the two collinear horizontal ones, is positioned in the middle of the horizontal side of the triangle [Figure 5.3]. These two

Hinged Connection I :Four Elements



1. **Horizontal Element I**

2. **Horizontal Element II**

3. **Diagonal Element I**

4. **Diagonal Element II**

Figure 5.4 | Decomposition of Hinged Connection I, scale 1:30

Hinged Connection I :Four Elements

total number of knuckles: 12
total width: 600mm

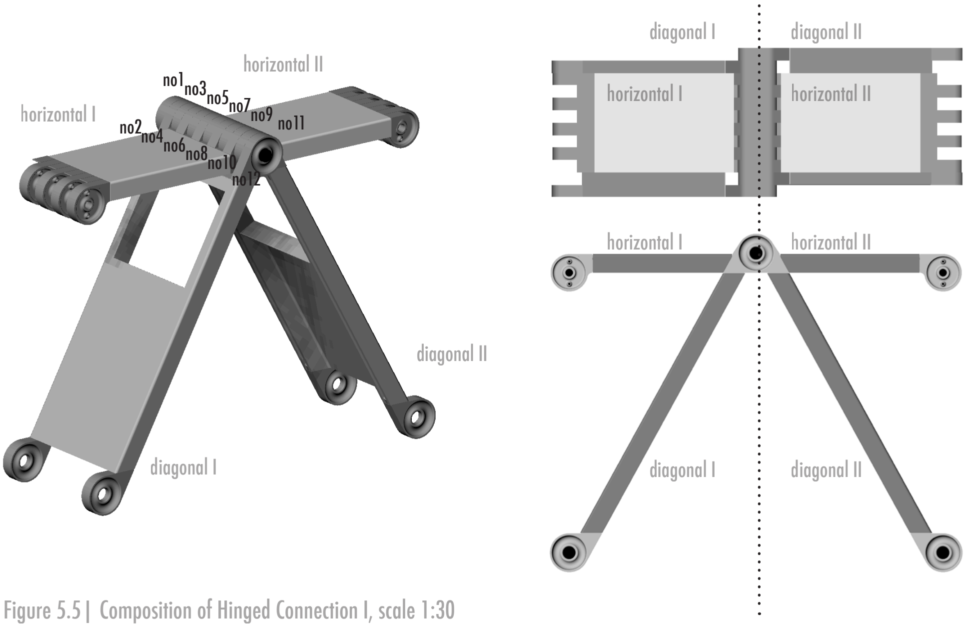


Figure 5.5 | Composition of Hinged Connection I, scale 1:30

connections are described further.

Beyond the hinged part, an important aspect is how these are connected and in general the composition of the structural members- links (or panels or leaves). Due to the need of simplicity, the variety of these members is limited to two types of panels: the *horizontals and the diagonals*.

In the proposed solution, extruded and casted aluminum for structural applications are selected for the panels and the connections respectively.

5.2.1 Hinged Connections

Most of the time, the designers and the users are interested only in the final, erected configuration of a structure. However, in deployable solutions, issues of deployment and erection are an integral part of the functionality of the product and of design feasibility, creating extra interest considerations. The goal for designers of a deployable structure should be to design the members for regular service loads and to obtain the deployability feature as a "bonus", without adding weight to the structure, and without decreasing significantly of its load bearing capacity. [5.11] This "bonus" is translated into the movable- kinematic joints.

Consequently, the movable joints are the most important aspects in motion systems in a view of kinematics. They must be constructed in such a way permitting relative motion in some directions while constraining it in others and simultaneously ensuring loads transfer.

One differentiates between fixed, pinned/hinged and free connections. The first ones allow no movement at all, denoting the closed connection between two or more consecutive structural elements in loadbearing hierarchy. Hinged connections allow rotational movements around the point of support and transmit horizontal and vertical forces. The third category of free bearings is able to translate and can therefore only support loads that are perpendicular to the plan of translation, typically gravitational forces from above. [5.12] In proposal folding design, the hinged solution is selected since the rotation is necessary. This hinge becomes a central feature of the concept proposed.

According to literature, there are three categories of hinged joints [5.11]:

1. Spherical hinged joints, which permit rotation in three independent directions,

Hinged Connection II: Two Elements

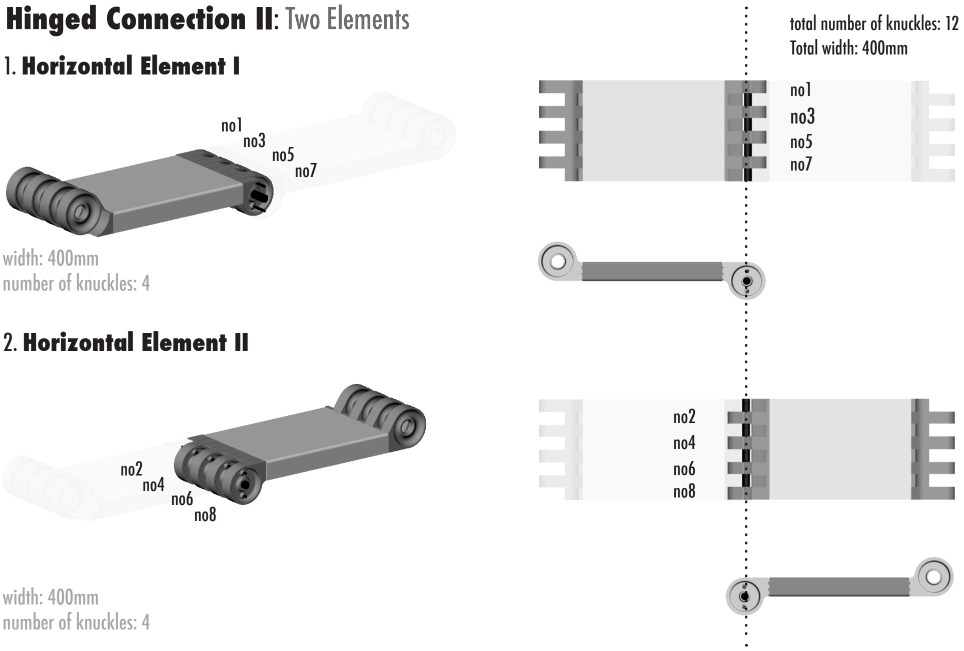


Figure 5.6 | Decomposition of Hinged Connection II, scale 1:30

2. Universal hinged joints, which allow two independent rotations and
3. Revolute hinged joints, where only one rotation is permitted.

Among these, here the attention is limited to revolute joints, which allows one rotation. Revolute joints are simple clevis-type hinges, which are also called rotary hinges. They allow one-degree-of-freedom movement (single movement) between two or more links that they are connected. The kinematic variable for a revolute joint is the angle measured around the two links. [5.11]

The *revolute hinged node* is the most complex element of the whole structure. It requires to be stiff and strong but also to permit rotation between multiple links, which follow different rotation angles and transitions in order to rise into their final compact position. Therefore, the right designing, dimensioning, positioning and materiality of it become very crucial.

The successful behavior, duration, reliability and foldability of a deployable structure depend on a great way in its joints, which require precise engineering details. Moreover, joints are points at which forces converge, and they must be able to resist and transmit those forces. The joints should meet the following criteria [5.13]:

1. Transmit the forces evenly throughout the components, which arrive at that point.
2. Firmly hold all the panels, which meet at that point.
3. Give every panel enough freedom to go from the close stage to the open one, but avoid holding them too loosely. Therefore, friction between the moving pieces should be minimized to avoid excessive wearing and to facilitate the erection and retraction processes.
4. As we deal with moving connections, it is important to take into account, that the transference of forces between bodies, which are not bonded together, can occur only by the pressure exerted by one body against another.

Terminology related to revolute joints [5.4] [Figure 5.4]

Pin: It is the rod running the length of the hinge. The pin holds the elements of the hinge together, allowing free rotation between them.

Knuckle: It is the hollow circular part of the hinge through which a pin is passed (sometimes called loop, joint, node, curl or protrusion). Knuckle length is the typical dimension- length of the knuckle measured parallel to the pin.

Hinged Connection II: Two Elements

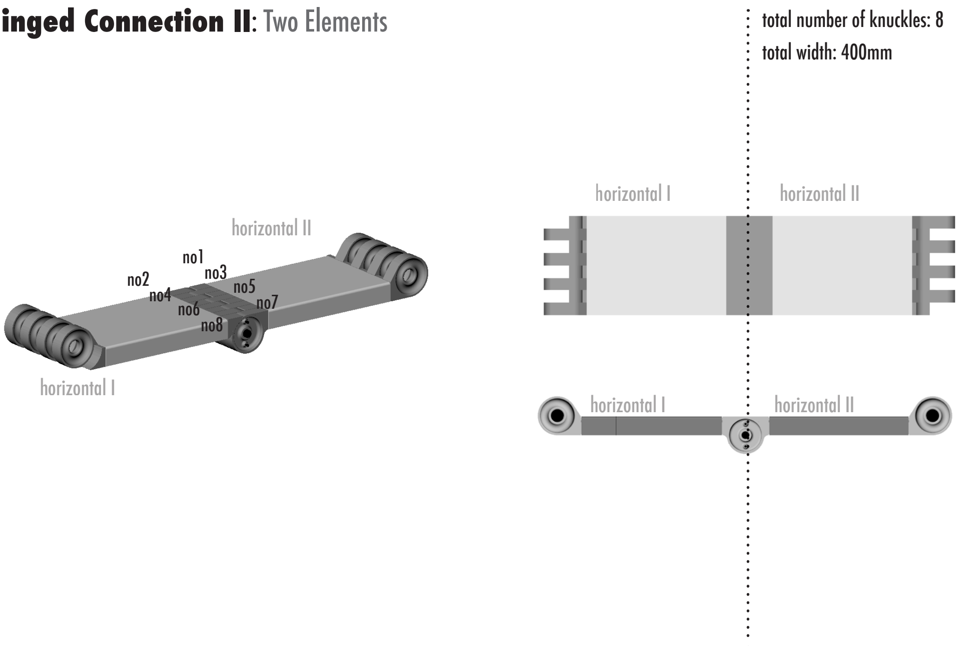


Figure 5.7| Composition of Hinged Connection II, scale 1:30

Notch: It is the space next and opposite to each knuckle. If we consider the hinge as a male- female system, the male parts are the knuckles and the female ones are the notches.

Leaf: Leaves are that portions of the hinge extending laterally from the knuckle.

Paint Clearance: It is the dimension between the outer face of the knuckle and the opposing edge of the leaf cutout over the entire range of rotation.

Back Angle: It is the angle described by the leaves when the hinge is fully open.

Locking: These systems are method of preventing leaf rotation.

There are different types of revolute joints regarding the number and the position of their knuckles and notches [5.4] [Figure 5.6].

In joint "X", the number of notches is one more than the number of knuckles and its both edges have notches. In contrast to type "X", the type "Y" is exactly the opposite configuration, where the number of notches is one less than the number of knuckles and therefore the two sides are ended up with knuckles. Finally, in type "H", the number of notches and knuckles are equal, creating leaves with notch on the one side and notch on the other. In this case, the facing members are identical.

In DeMoLi design, all the horizontal elements have four knuckles and four notches following the "H" type; while the diagonal ones have only two knuckles at their end sides according to "Y" type and one big notch between them that is equal to the length of the horizontal leaves.

Knuckles have a cylindrical form, with diameter of 150mm in hinged connection II and 156mm in hinged connection I. Their width is 48mm, 2mm less than the width of notches, which works as a clearance. Opposite to them, the notches are formed by the negative shape of cylindrical knuckles, working in this way as stoppers that prevent the element from rotating fully and hold them in a resting position. [Figure 5.10 and 5.11]

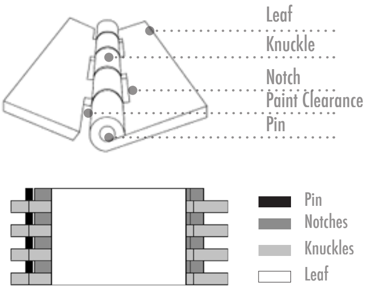


Figure 5.8| Terminology related to revolute joints [5.4]

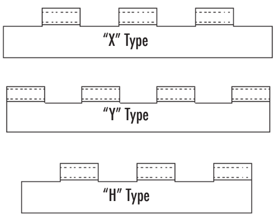


Figure 5.9| Types of revolute joints [5.4]

Hinged connection I receives four elements: two horizontals and two diagonals. It has 600mm width consisting of 12 knuckles in total; eight for the two horizontal elements and four from the two diagonals, as it is shown analytically in Figure 5.4. To allow the structure to deploy, each horizontal element has a mid-length hinge.

This hinge is the type II *(hinged connection II)*, which consists of eight knuckles, four from each element and total width of 400mm. [Figure 5.6 and 5.7]

The basic requirement of the hinged connections is that they must be able to accommodate geometrically the rotation of the member that takes place during deployment process. These can influence the packaging efficiency of the structure. When synthesizing motion structures, the positions and operations of the parts during the motion are far more important than other physical properties such as velocity and acceleration, as the cycle time of motion structure is generally in a matter of minutes or hours rather than seconds or less like conventional mechanisms. [5.10] In DeMoLi case, this depends on the position of the rotation axes. Hence, the careful placement of the rotation axis means that when panels folded out are formed a normal bridge and when folded in they occupy as less space as possible creating an “airtight” shape.

The position of the axes is defined by two parameters. The first is the direction of the movable elements (upwards or downwards) and the second is their final position. Since the elements have a certain thickness by positioning the axis to their upper side of this thickness, the upward movement is permitted. Conversely, by positioning it to the lower side permits the downward movement. Furthermore, the offset of the axis defines the distance between the two folding parts.

The centerline of pin in hinged connection I, is located 3mm above the upper side of the horizontal panel due to the upward movement of these elements and the preset distance of 6mm that are needed in their folded configuration. These distance results from the double thickness of the diagonal elements when they are positioned in their compacted configuration. (Each diagonal element leaf has 3mm thickness). Consequently, in the compact state the horizontal elements in hinged connection I have a between distance of 6mm, while the diagonal ones are totally flat. [Figure 5.12]

The rotation axis in hinged connection II is positioned collinear the lower edge of the thickness of their plates. In this way the two horizontal leaves can be folded upward from 180 to 0 degrees, and they are ended up “in touch” configuration without any space between them.

5.2.2 Leaves

In the first part of Detailed Design Phase, hinged connections were described. This section is referred to the rigid elements- leaves that connect the hinges. The leaves are “rigid” parts, stiff and accurate in shape, arranged in such a way that the transformation from a compact configuration to a deployable one is possible. For standardization reasons, the whole structure consists of two types of leaves: *the horizontals and the diagonals*.

As it was described in Design Testing Phase, the selected material is structural aluminum. Leaves are shaped as extrusions, which are prismatic, linear components with a constant cross section over their entire length. The range of section geometries extends from regular shapes, like H-sections to really complex customized solutions. The development of cross-sectional geometries results for the need for more efficient and lightweight elements and therefore the potential design is exploited to the full in terms of efficiency, weight and cost.

The general concept of the two types of leaves lied to the ability of the two horizontal elements to be folded inside the diagonal one creating a fully compact configuration. The detailed explanation of the horizontal and diagonal leaves is explained deeply in the following section.

Due to the fact that leaves for the DeMoLi Bridge are individual, customized pro-

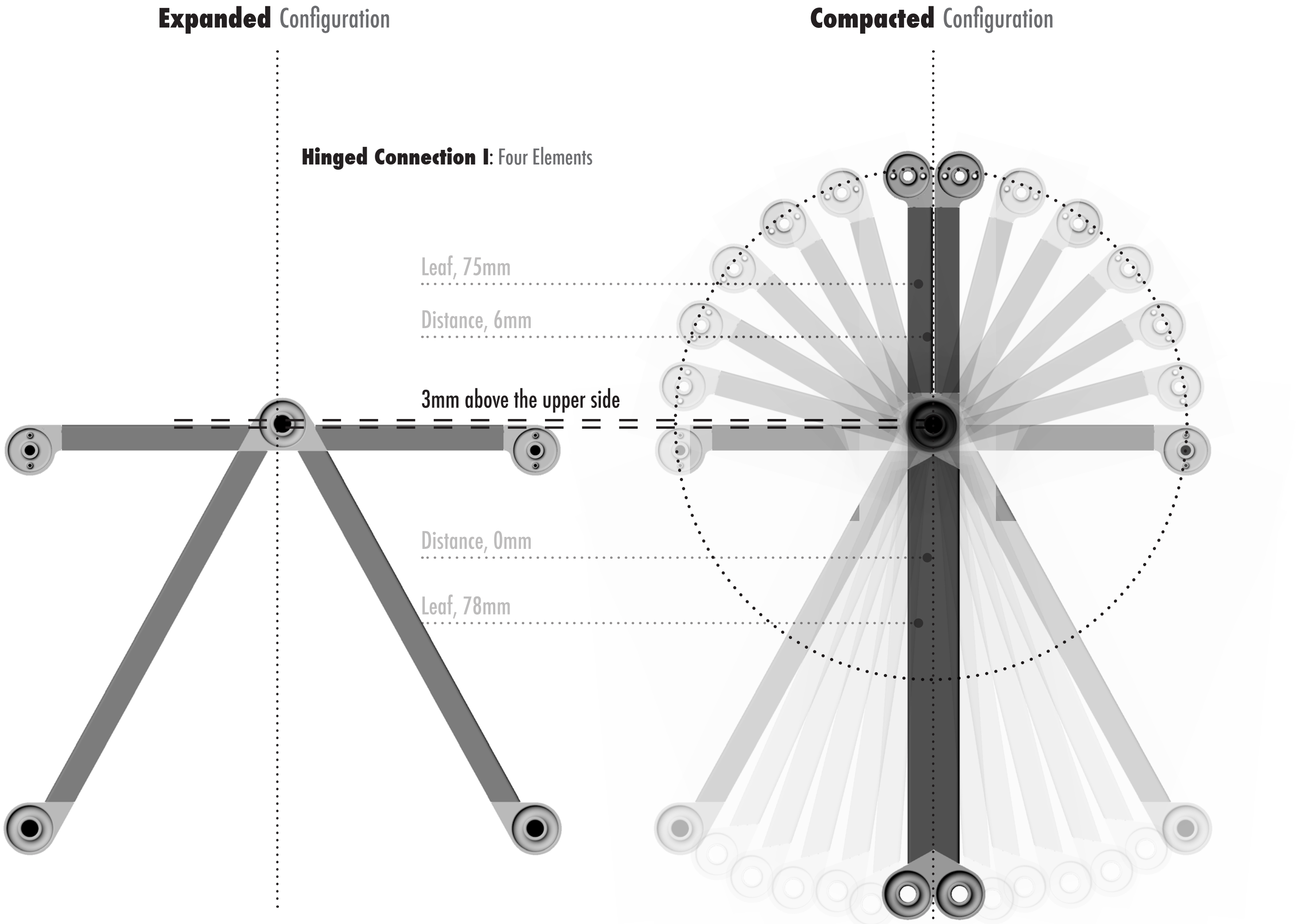


Figure 5.12 | The position of the rotation axis in hinged connection I, (3mm above the upper side), scale 1:20

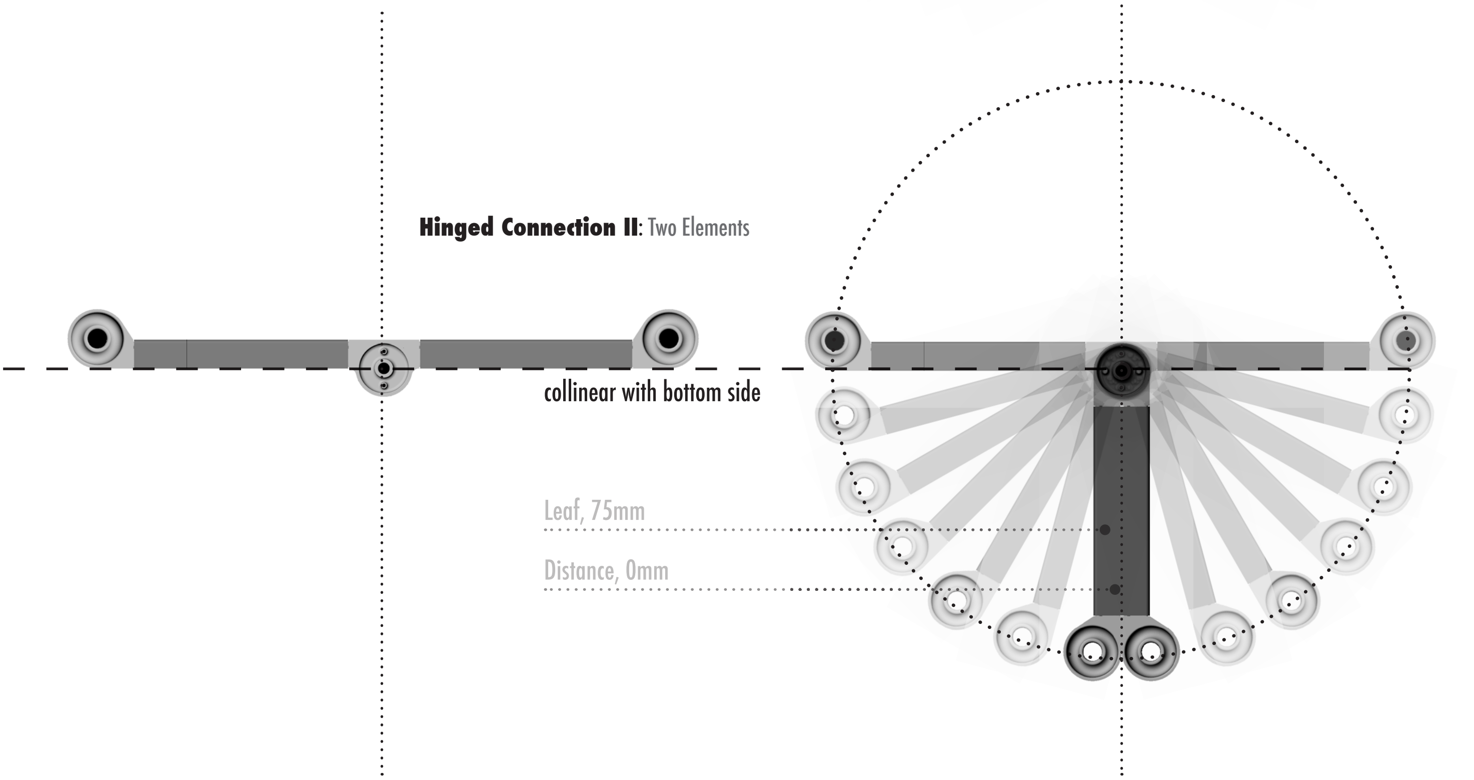


Figure 5.13 | The position of the rotation axis in hinged connection II, (collinear with bottom side), scale 1:20

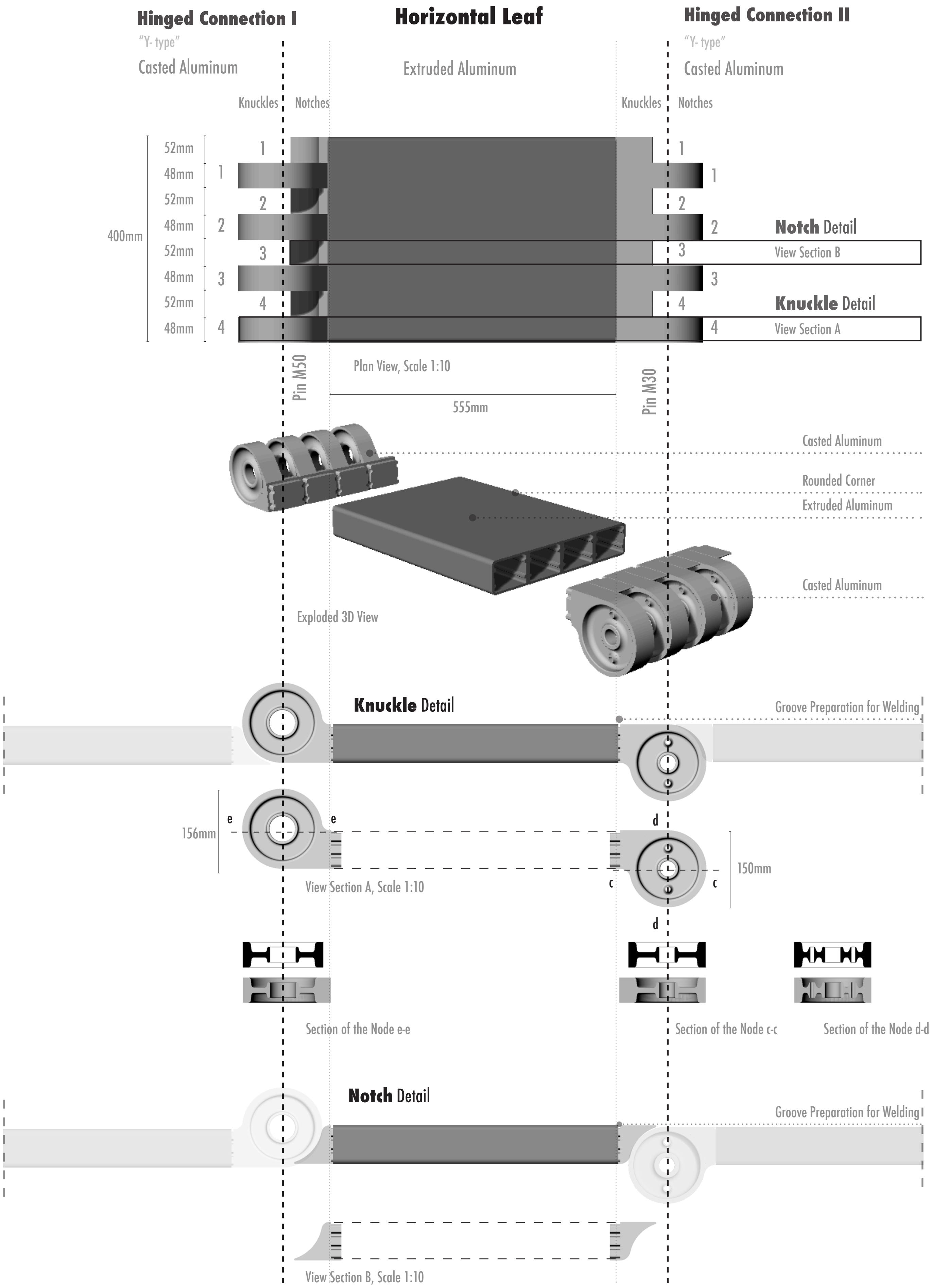


Figure 5.10 | Explanation of Horizontal Leaves

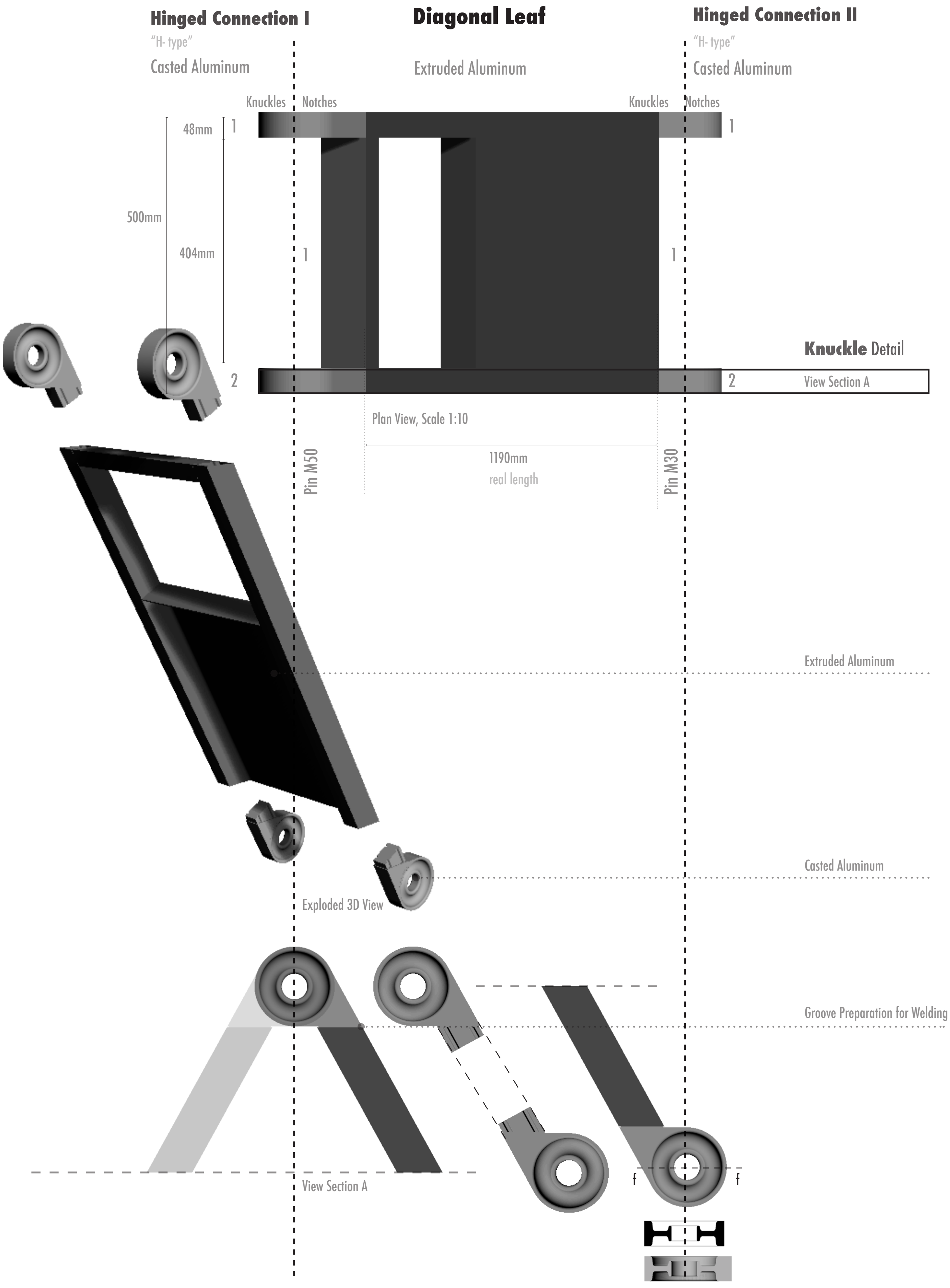


Figure 5.11 | Explanation of Diagonal Leaves

files, several rules and recommendations with respect to costs and feasibility are presented:
1. Profiles with a uniform wall thickness are simpler to produce.
2. Hollow profiles increase die costs and are more difficult to produce. So, the desirable profiles are the solid ones and if the design requires hollow profiles then the goal will be to use as fewer cavities as possible[1].
3. Peaks and corners have to be rounded. A radius of 0.5 – 1mm is often sufficient.
4. The extrusion has to be as symmetrically as possible.

The section of horizontal leaves is shown in Figure 5.14. The selected profile class for these elements is semi-hollow profiles, taking their advantage of cost-efficient solution in combination with the axial loading. The only parameter that influences the load bearing capacity of the elements subjecting to axial forces is the area of the cross section.
So far, the leaves are formed with four “voids” where the protrusions of casted aluminum are inserted and then welded together. Each void has a drafty width of 100mm and the overall width of the leaf is ended up to 400mm.
The thickness of the section elements is uniformly and according to the calculations in Design Verification Phase is equal to 5mm. Finally the overall height of the panels is 75mm.
The section of diagonal leaves can be characterized as a hollow section[2] with U shape. The two vertical members of the U shape are hollowed in order to receive the protrusions of knuckles from hinged connections, while the space between them accommodates the horizontal leaves in their compacted state. In order to reduce the packing volume this horizontal part has only 3mm thickness. Enhancing the connection of the thin plates and the vertical members, a rounded corner of 10mm is applied to the internal surface of the leaf. The same rounded corner is also applied to the external surface of the horizontal leaves.
The total height of the diagonal leaves is 78mm, 3mm more than the horizontal ones, which is the thickness of the elements of diagonal leaves. Consequently, in their folded configuration, the horizontal leaves are inserted inside the diagonal ones creating a fully compact configuration with 78mm total height, equal to the height of the diagonal leaves.
Finally, the width of the diagonal leaves is 550mm, which is equal to the width of the horizontal leaves (400mm) plus two knuckles (2x50mm) plus the knuckle of the opposite diagonal element (50mm). A detailed view of a diagonal leaf is shown in Figure 5.14.

5.2.3 Pin Retention

Both hinged connections are inseparably connected by a steel pin that runs the entire length of the hinge. The diameter of the pin is calculated according to the axial forces of the links of DIANA structural analysis of the truss and the ultimate shear stress of the steel, which is the 0.58 of the tensile yield strength of the material:
Ultimate Shear Strength= 0.58 x Tensile Yield Strength
Tensile Yield Strength for steel: 310MPa
0.58 x 310MPa= 180MPa (N/mm^2)
Regarding these, the minimum allowable area of the pin is calculated by dividing the ultimate shear strength of the steel with the shear force that is exerted on the pin from each knuckle by the formula:

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[1] For the definition of solid and hollow section see pp. 114-116.

[2] For the definition of solid and hollow section see pp. 114-116.

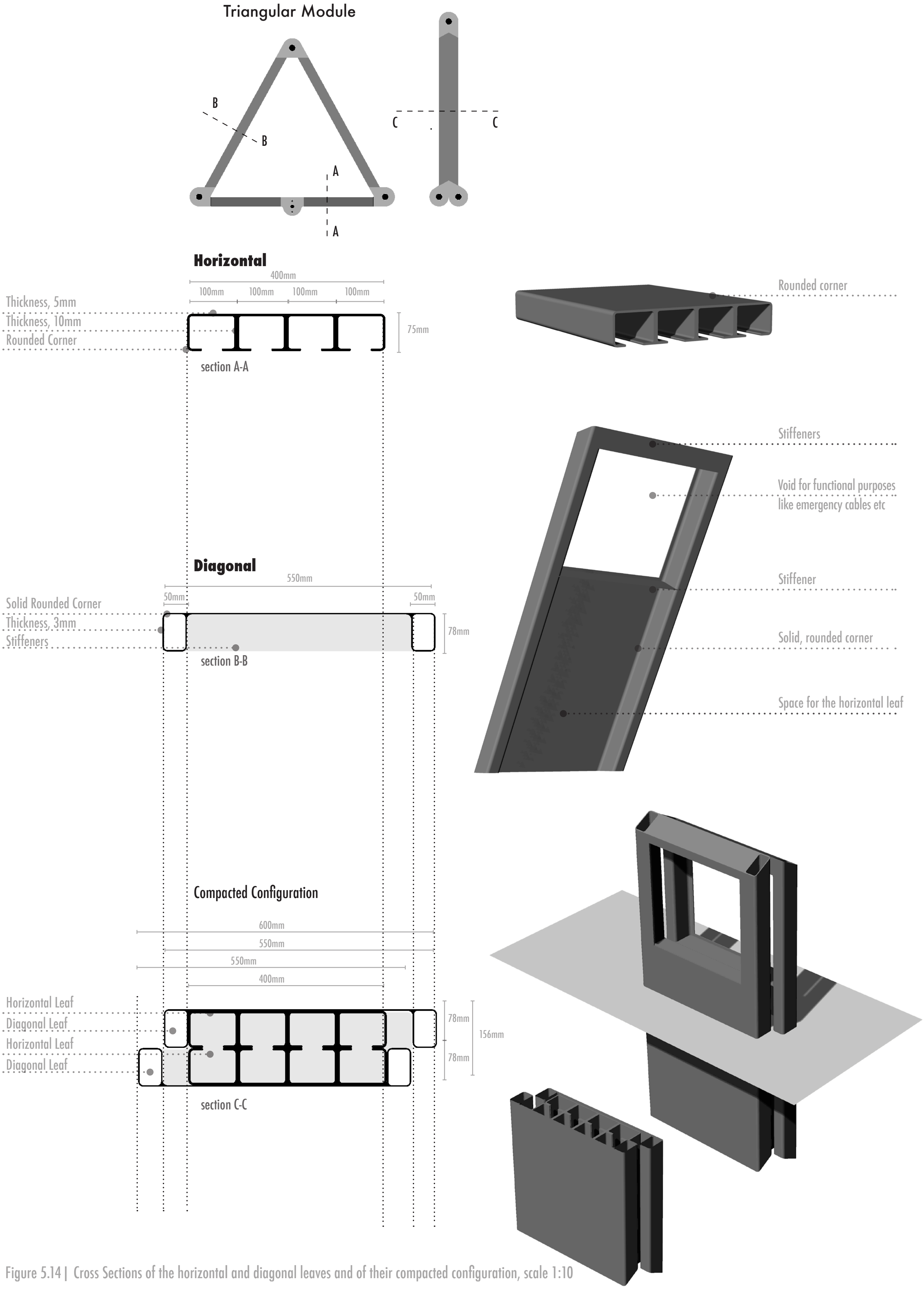
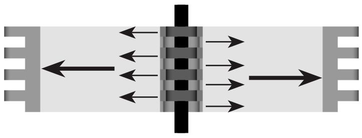


Figure 5.14 | Cross Sections of the horizontal and diagonal leaves and of their compacted configuration, scale 1:10

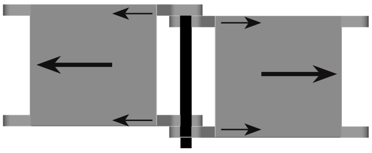
Horizontal Element



Ntot= 985000N
n= 4

F= Ntot/knuckle= 300000N

Diagonal Element



Ntot= 480000N
n= 2

F= Ntot/knuckle= 240000N

$\tau=F/A$
Where,
τ: Ultimate Shear Strength,
A: Area of the pin ($A=\pi R^2$) and
F: Shear force of one knuckle
The shear force is calculated from the maximum tensile/ compression force on the links of the structures divided by the number of knuckles, F=Ntot/ n,
n=4 for horizontal elements
n=2 for diagonal elements
The maximum axial force (N) of horizontal elements according to the Diana results is presented in LC2 and is raised to 985000N. In order to define the shear force that is exerted at the pin, the last number is divided by four, which is the number of the knuckles of the horizontal leaves.
$F= N/4= 985000/4= 250000N$
$S= 180N/mm^2$
$A= 1400mm^2$
$R_{min}= 21mm$
For the diagonal elements the axial force is less in comparison with the horizontal one, however there are only two knuckles (n=2) and therefore the pin's diameter is tested separately. The maximum axial force for the diagonal elements is equal to *480000N.*
$F= N/2= 480000/2= 240000N$, which is less than the previews shear force acting due to the horizontal elements and it doesn't need further consideration.
According to these calculations, the minimum allowable diameter of the pin is 21mm. For the proposal design, pins of 30mm and 50mm are used for the hinged connections II and I respectively. For the hinged connection I, a bigger diameter is selected because it is also the supporting point of the decking system.
The types of pin connection are categorized to how they are connected to the main joint[3]. Some of them are more permanent while some other permits the disassembly. The focus here is on the second category because the ability of the same truss to adjust in different applications requires a temporary solution. The proposal solution is a splined pin connection, where the splined portion of the pin is slightly larger than the inside diameter on the curl of the hinge. Thus, it is press fit and remains in the knuckle.

5.2.4 Locking System

An important difference between the deployable structures and the conventional ones is that they are discontinuous due to their movable joints. Consequently, most of the time the stability of hinges must be ensured by locking them in plane when the structure is fully deployed. By doing this, the initial discontinuous elements are locked and therefore the structure behaves as a single continuous system.
The deployable structures are classified into group, on the basis of their locking

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[3] Types of pin connections related to their connection with the revolute joint [5.4]:
Staked Pin: Depressing the knuckles of one leaf to secure the pin and to prevent axial movement in the knuckle.
Coined Pin: One end of the pin is deformed and when driven into the hinge, it wedges in place.
Ends Crimped: The pin is cut shorter than the hinge and centered. Then both end knuckles of the hinge are crimped to prevent the pin from coming out.
Bent Pin: The pin is usually cut longer than the hinge and bent 90 degrees. This permits easy assembly and disassembly but no security.
Flush Pin: There is no pin retention here except for the friction between the pin and the inside of the curl. This can vary greatly depending on how tight the hinges have been curled.
Welded Pin: One or both ends of the pin are welded to the end curl. This is a very secure but permanent method of pin retention.
Spun Pin: Cold forming of one or both ends of the pin to a diameter greater than the inside diameter of the knuckle to prevent axial movement. This is also known as peened ends.

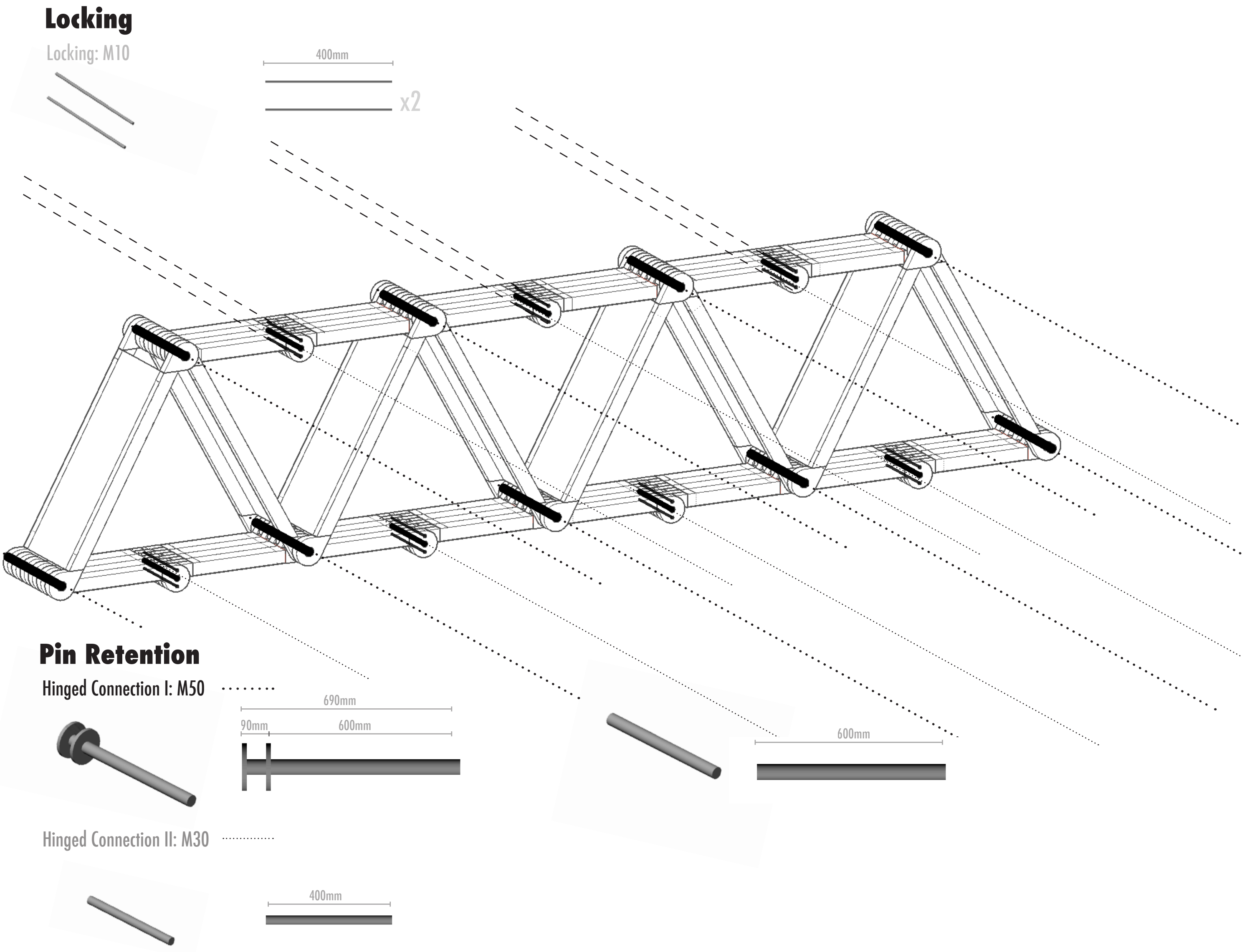

Figure 5.15 | Visualization of the pins and the additional locking systems

system. Some of them, called manually locking structures, behave as structural mechanisms during deployment and need the addition of new members in order to be fixed in the deployed configuration. This increases the effort required for erection and dismantling. Others, so-called self-locking deployable structures avoid this problem by incorporating their locking mechanism in the structure and its movement and thus, they are locking automatically when closed. This automatic action operating with minimal human intervention but requires either extra technologies and subsequently a more expensive solution or members with residual stresses, which decreases the load capacity of the structure due to the buckling of the elements. [5.11]

Referring to the DeMoLi Bridge, the system behaves as stress-free mechanism during its moving process and therefore needs to be stabilized. In order to overcome this problem, the geometry of the hinges and more specifically the shape combination of knuckles- notches helps to “lock” the structure. However, due to the fact that a high precision is required, latching elements must be incorporate in the design of the joints.

Between the different types of locking system, the manual way is the selected one as a simple and cost-efficient solution. More specifically, two additional external pins are fitted within hinged connections II after the structural net is opened, giving 100% security and ensuring the position of the nodes even if there is an upward force. The locking system is applied only on the upper chord because the hinges to the lower chord lock by the deck panels. The two pins are also used during the transportation, locking the structure in the compact configuration. The locking pins are made of steel with diameter of 10mm, while their holes are slightly bigger for tolerances (12mm). Hence, the folding truss is able to “lock” in its two extreme configurations.

5.2.5 Tolerances

Hinges must be able to sustain strong loads but simultaneously to move freely while external forces result in friction at the points where the two elements are in touch. Hence, the good function of motion structures includes regular lubrication of the bearings and design of their clearances to ensure that the mechanism will remain throughout its working life strong and stiff enough to withstand all the forces it will experience [5.10] but also to ensure smooth and noise-free operation. Maintenance-free bearings are also available, for example Teflon-coated plastic [5.12].

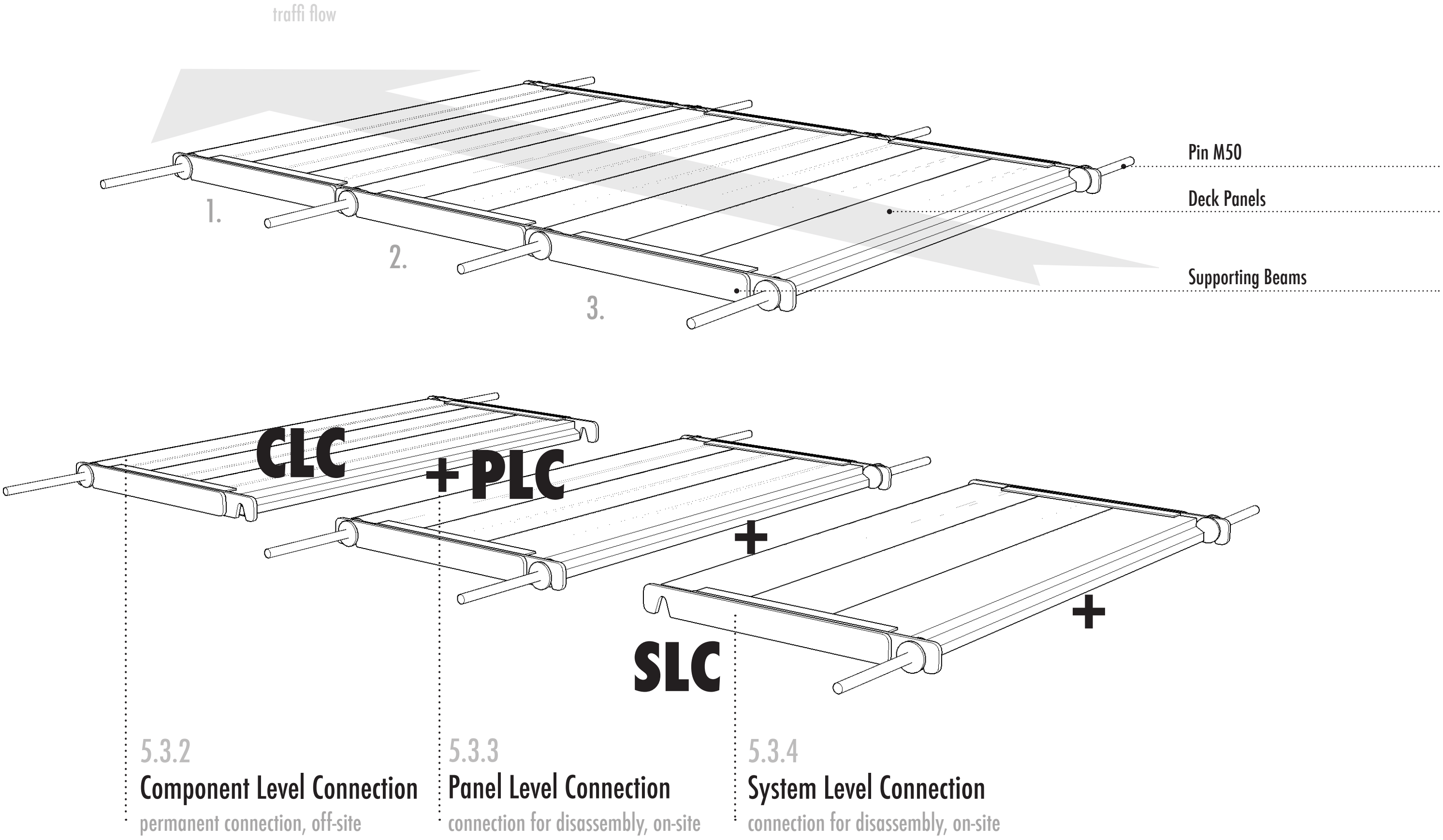

Figure 5.16 | The three connection levels in DeMoLi bridge

5.3 Decking System

5.3.1 Connection Levels

Decking system consists of identical panels, which are positioned next to each other, following the rules of modularity. Each panel has a width of 3300mm, creating the required notional width of 3000mm and weights approximately 300kg, namely 200kg/m. Its length is about 1500m, which is the distance between the two supporting points. The bridge deck panels are developed entirely by using aluminum extrusions, while the connection with the truss is achieved also by aluminum profiles in longitudinal direction of the truss.

The bridge deck distributes the load from vehicles and pedestrians to the longitudinal girders and then on to the abutments. In general, it is designed under the guidelines of the philosophy to reach the specified limit states through the objectives of safety, serviceability and constructability with regards to the issues of durability, inspectability, lightness and economy.

In decking system, the connections are limited to few easy understandable systems. For the off-site joining the selected technique is welding, while for the on-site one is mechanical fasteners, facilitating the erecting process. In general, the connections for bridge decks include primary and secondary load-carrying joints, which are further subdivided. The focus here is on the following three levels [5.5] [Figure 5.16]:

1. Component to Component Connection to form modular bridge deck panels and henceforth referred to as Component Level Connection, CLC,

2. Panel to Panel Connection to form bridge deck systems and henceforth referred to as Panel Level Connection, PLC and finally,

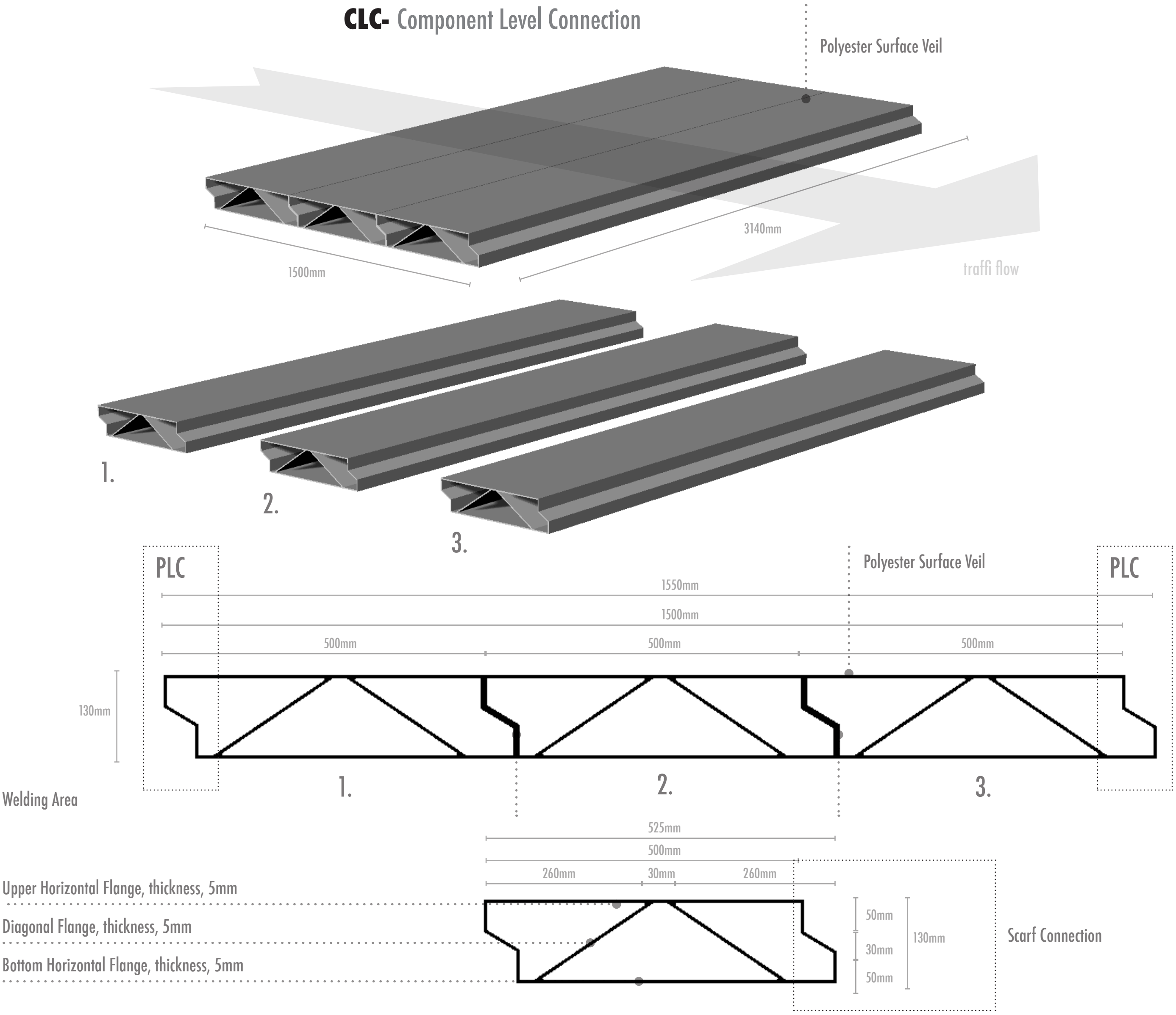

Figure 5.17 | Configuration of Component Level Connection, scale 1:10

3. Deck to Support Connection to form bridge superstructures and henceforth referred to as System Level Connection, SLC.
The choice of the suitable means of connections represents a compromise between optimizing the transfer of forces and the robustness and reliability of the design. Another aspect, to be considered for temporary structures like DeMoLi, is the detachability of Panel and System Levels Connections [5.2]. In Component Level Connections, the main objective is to ensure the integrity of the deck panel and the load transfer efficiency between the jointed components. In Panel Level, major concerns are the deck system load transferring and carrying capability. Finally, in System Level Connection, shear transfer and connection constructability with the superstructure are the main focus [5.5].

5.3.2 Component Level Connections (CLC)

There are several existing systems employ a modular design for deck bridge applications. The proposal one, which results from the structural analysis during the Design Verification Phase, is a multicellular panel made of extruded profiles.
In general, current commercially available decks for rehabilitation and new con-

PLC- Panel Level Connection

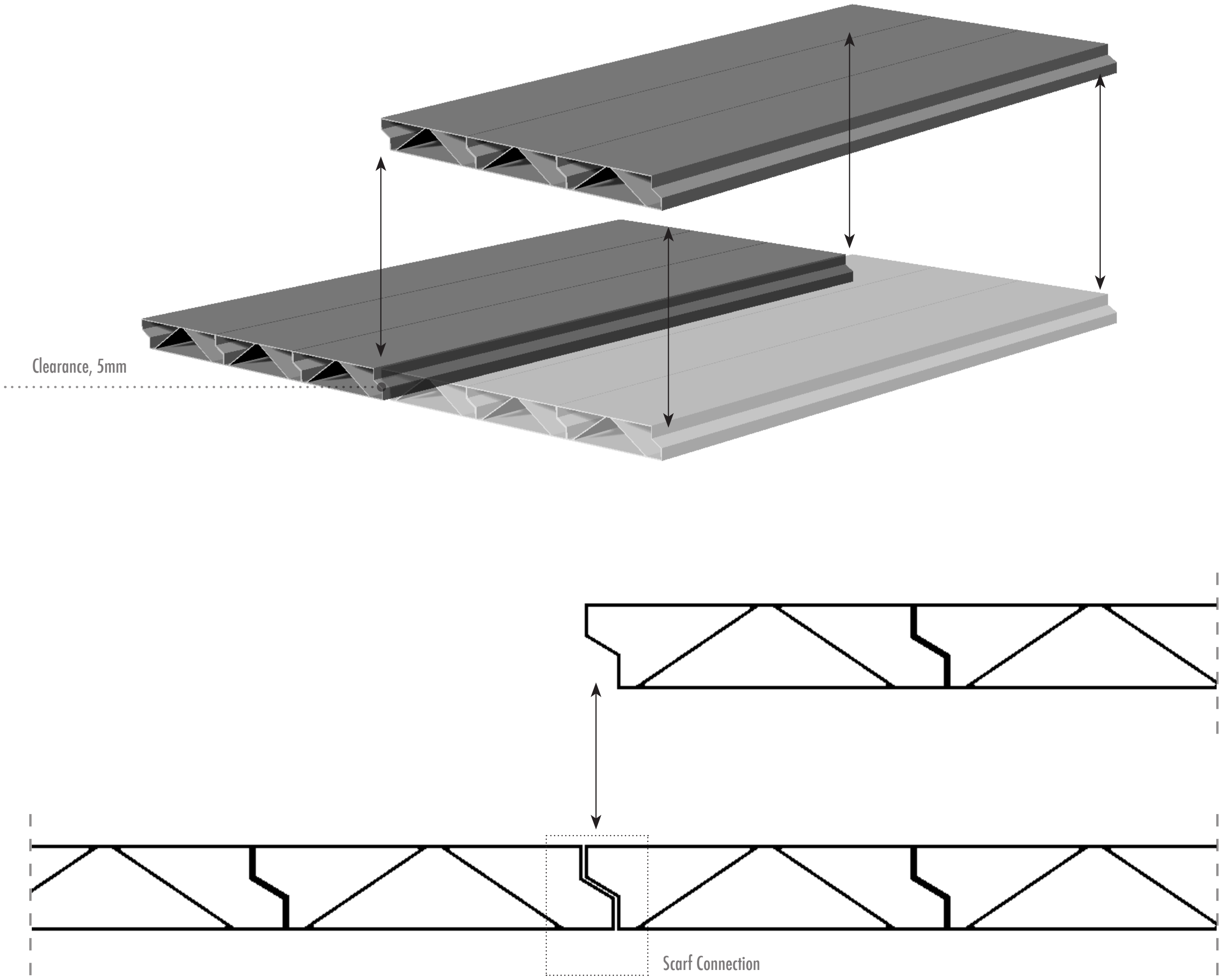

Figure 5.18 | Configuration of Panel Level Connection

struction can be classified into two categories according to the types of assembly and construction: sandwich panels[4] and extruded profiles. The proposal solution focuses on multi-cellular- extruded design, mainly due to its geometrical variety that facilitates the assembly processes on and off site. [5.5] Furthermore, they are the most cost-effective way to manufacture constant cross-section profiles. This process is highly automated and uses low-cost forms of raw material.

The general dimensions of one deck panel are 3140mm x 1550mm x 130m. Each of this is composited of three identical extruded profiles creating a truss-like, orthotropic bridge deck[5]. [Figure 5.17]

The three extrusions result from fabrication limitations. Specifically, the allowable maximum length for hollow shapes with height larger than 60mm is 600mm.

Due to the advantages of simplification in design and assembly, welding is generally used in CLC for connecting permanent aluminum deck components form-

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[4] Sandwich panels have two basic forms: foam core sandwich panel and honeycomb sandwich panel. Its mainly advantage is to carry loads in both directions with the same stiffness, which is ideal for carrying the wheel loads of vehicles [5.2]

[5] Decks with different stiffness in longitudinal and transverse directions are called 'orthotropic'. If the stiffness are similar in the two directions, then the deck is called 'isotropic'.

ing bridge deck sections. For the bridge deck to be structurally effective and to achieve composite action, the profiles must be joined transversely. [5.6] Thus, the succession prismatic sections are welded at their sides and the bottom and upper longitudinal line.

In DeMoLi deck, the extruded profiles have sections 550mm width; 130mm height and they are 3140mm long according to the width of the bridge. Additional diagonal elements are enhancing the stability of the structure creating a triple-hollowed section, as it is shown in Figure 5.17. Furthermore, they form a scarf connection facilitating both Component and Panel Level Connection. Although, the CLC could be more complicating forming a more tightly connection between the extrusions, due to the modularity and the requirements of temporary PLC is limited to very simple scarf sections. The scarf is formed with inclined protrusions and recesses, where the protrusions are laid on the recesses.

The profiles have a uniform wall thickness of 5mm making the production process easier and more economically.

Finally, a polyester surface veil is added for protection and surface finishing.

5.3.3 Panel Level Connections (PLC)

The main objective for Panel Level Connections is the efficiently transformation of the stresses between jointed panels to the main beams of the structure, as well as the easy on-site installation. [5.5] Although, in Panel Level Connection, the joints shall be designed to provide enough connecting force and maintain the integrity of the Panel-Connection-Panel system, in DeMoLi case, there is no direct connection between the decking panels, because as it will be explained latter, each of this panel is self-supported. In this way PLC provides the possibility of a really fast and easy erection, disassembly for re-location and repair.

Also a small clearance between the elements of 5mm is applied as a tolerance. [Figure 5.18]

5.3.4 System Level Connections (SLC)

Deck panels are connected to their supports to transfer loads transversely to the supports that bear on abutments. The design of efficient deck-to-support connections is the most challenging topic in the development of bridge deck connections, especially in the case of fast and demountable solution.

The SLC in DeMoLi design includes the construction of longitudinal aluminum beams at both sides of the deck panel, which are welded with it. These beams are used to connect each panel deck with the truss. Specifically, the panels rests on the pins of the hinged connection I at the bottom chord of the truss.

As it is seen in Figure 5.19, the longitudinal beams consist of three profiles. The first two are used as connectors with the truss pins. They are formed in the same way, with 1490mm length and they are welded together creating a beam of 1750mm. This complication is needed because each pin supports two sided panels. Moreover, they are shaped in such a way facilitating the erection process by using clearances and rounded ends. For the connection with the pin a slot instead of a hole is designed for the same reason. Thus, during the launching and after the deployed of the trusses in a preset distance, the panels are inserted through a downwards movement to the pins one by one. The second element has a U section shape and connects the deck panel with the former beams in a sufficient way working as moderator between them.

To sum up, all the connection that are realized on-site, are based on rapid assembly, and there is also possibility for manual handling.

SLC- System Level Connection

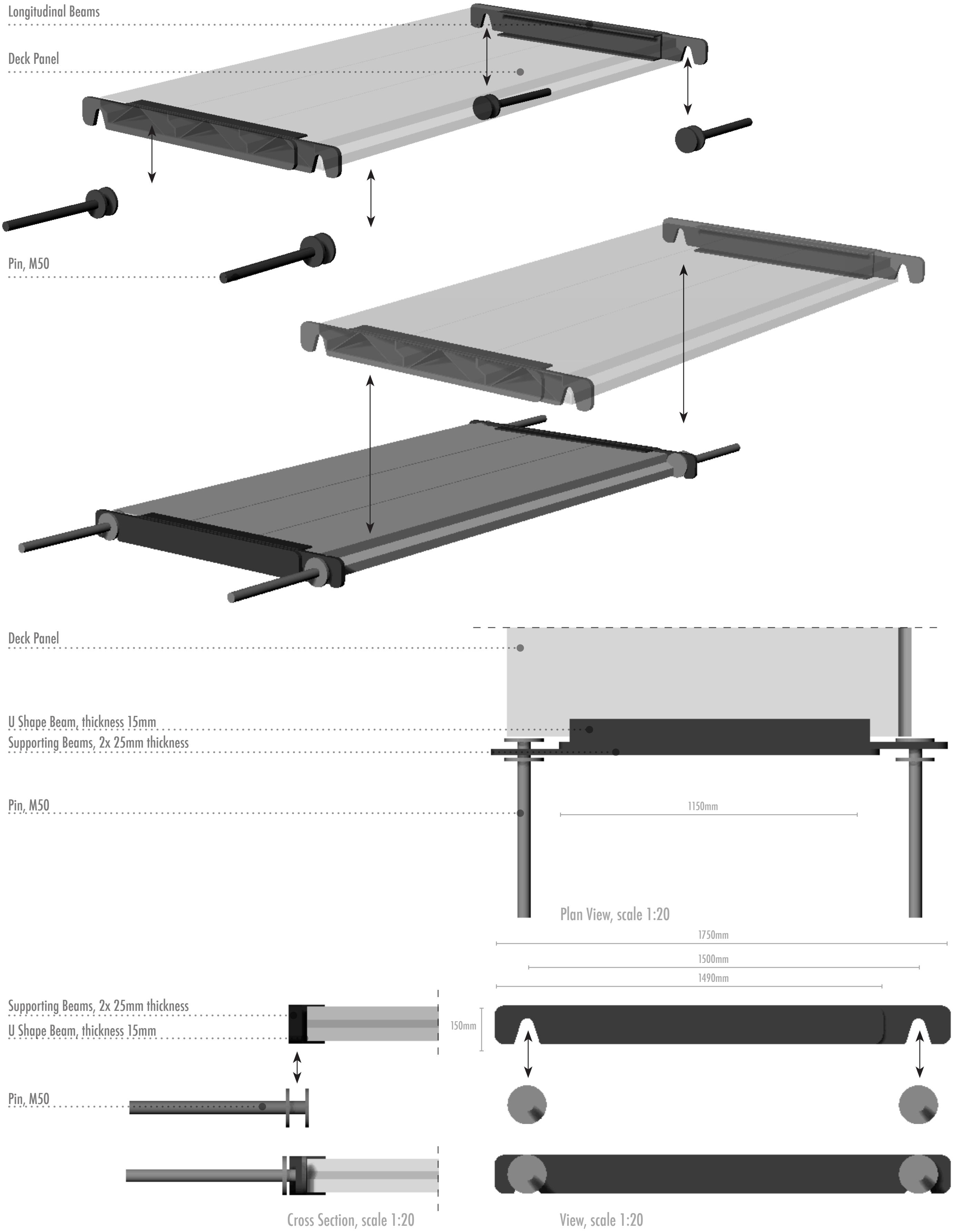

Figure 5.19 | Configuration of System Level Connection, scale 1:20

5.4 Bridge Bearings

A bridge bearing is a component of a bridge, which typically provides a resting surface between shore or bridge piers and the bridge superstructure. It carries the reaction forces to the foundations and controls the movement of the bridge. The purpose of a bearing is to provide freedom to some displacements and rotations and thereby reduce the involved stresses on both superstructure and substructure due to constraints. Movement could be thermal expansion or contraction, or movement from other sources such as seismic activity.

There are several different types of bridge bearings, which are used depending on a number of different factors, such as the bridge span, etc. The oldest form of bridge bearing is simply two plates resting on top of each other. A common form of modern bridge bearing is the elastomeric bridge bearing[6]. Another type of bridge bearing is the mechanical bridge bearing, which are further categorized into several types, like the pinned bearings, which in turn includes specific types such as rocker and roller bearings.

In DeMoLi Bridge the bearings are simple rockers, which allow free rotation about a single axis but not movements. Rockers are stout mechanical bearings using pins to permit translation (movement). The pin that is used in the proposal solution is the pin from the hinge.

Specifically, bearings are also part of the pre-assemblying process and they are incorporate into the last and first bottom hinged connection I. They are formed with five knuckles at the points where there are no protrusions of the hinge and thus, they are bounded with the hinged connection. Additionally, there are two base plates of 10 and 50mm thickness.

After the final erection and location the base plate is bolted to the ground through three M39 bolts.

5.5 Access Ramp

Due to the fact that there is a small step between the shore the upper deck level, a ramp is used to achieve a smooth access on the bridge especially for the vehicles. The ramp is also pre-fabricated and pre-assembled in the factory.

The applied system is very simple. Six aluminum plates of 10mm thickness, 500mm width and 600mm length, are connected to the longitudinal beams of the SLC though a pin with 20mm diameter, which allow free rotation. In this way, hinged access ramps are created. During the transportation the ramp is folded on the upper surface of the deck and after the final installation is rotated in order to reach the shore. The end ramps sequence allows easy transition on undulating surfaces. Due to the fact that the created gap could vary in each application, the length of ramp is equal to 600mm, with the maximum allowable inclination of 30%.

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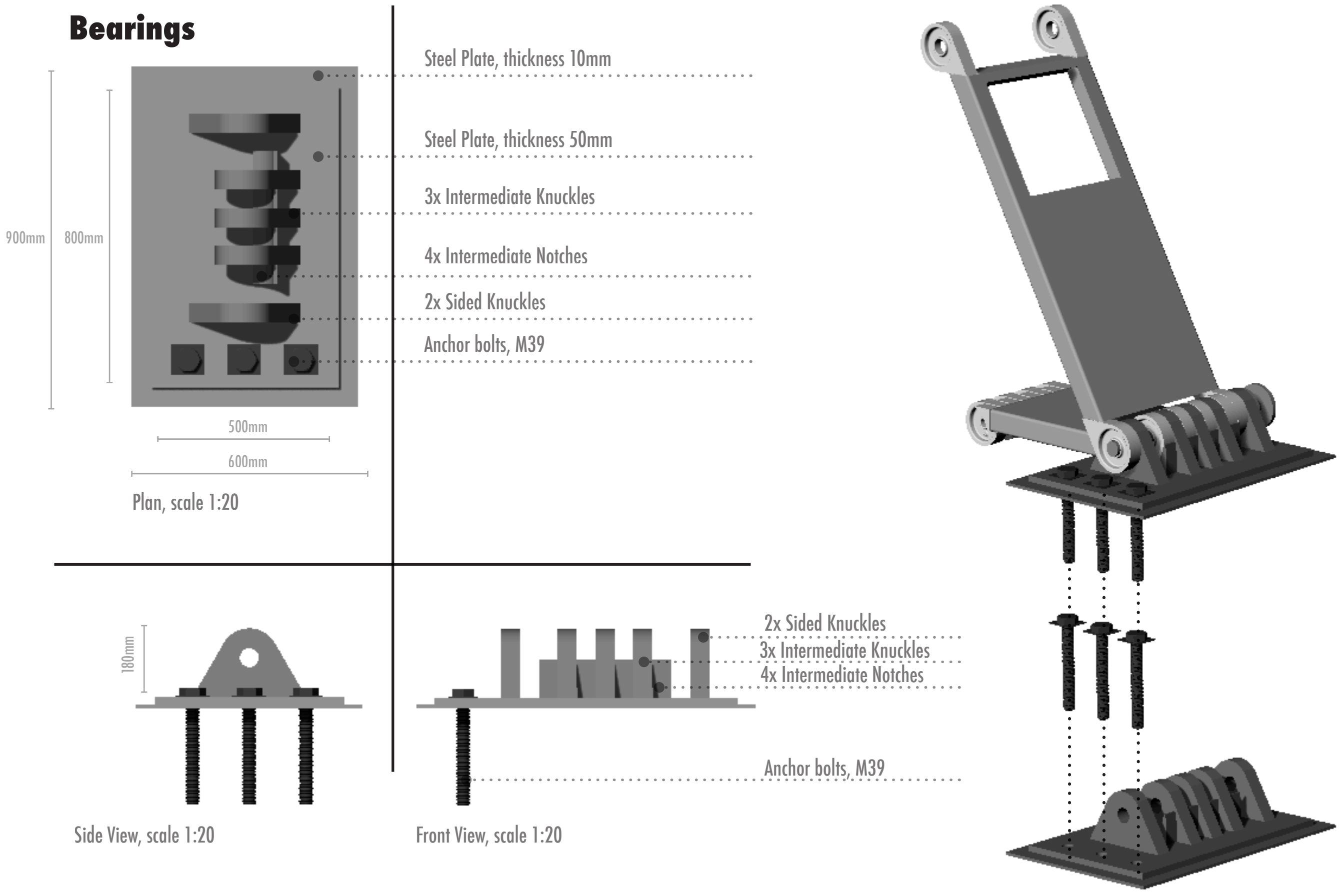
[6] The elastomeric bearing allows the deck to translate and rotate, but also resists loads in the longitudinal, transverse and vertical directions. Loads are developed, and movement is accommodated by distorting the elastomeric pad.

Bearings



Plan, scale 1:20

Side View, scale 1:20

Front View, scale 1:20

Figure 5.20 | Bearings

Access Ramp

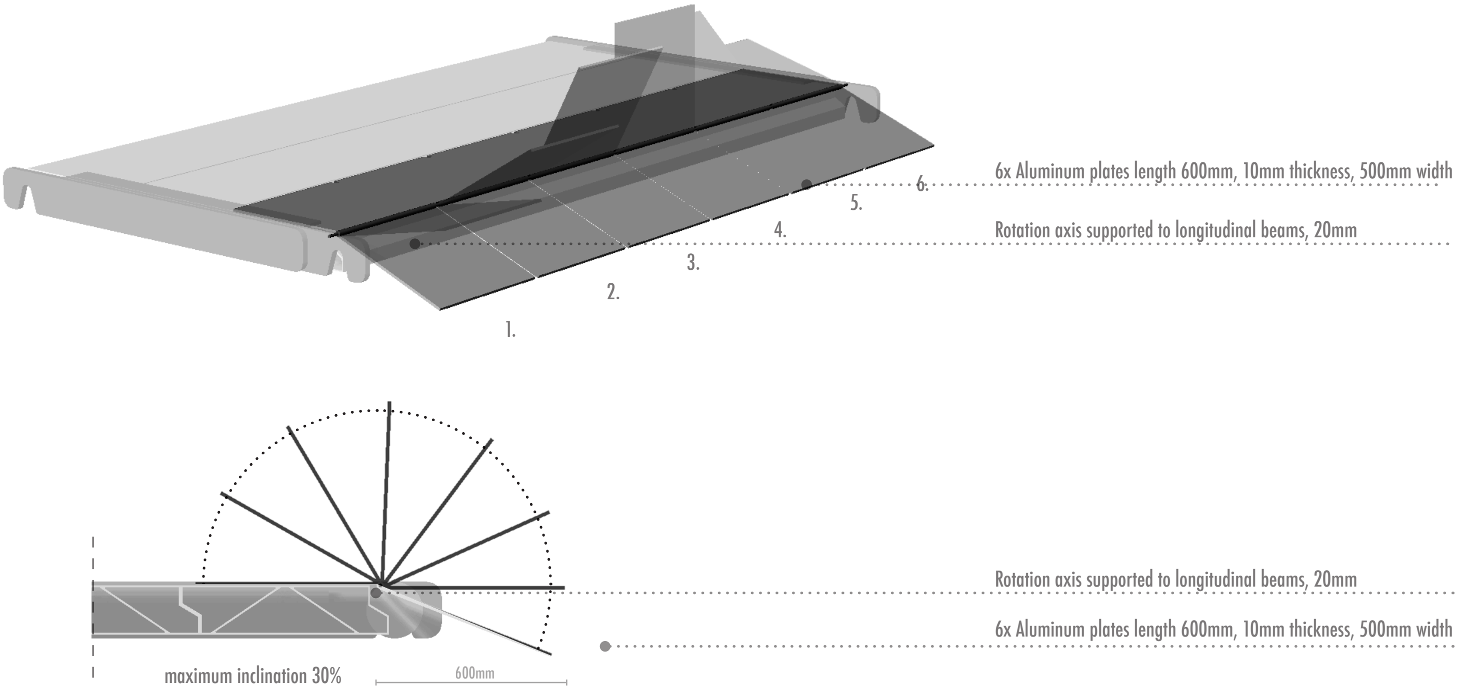
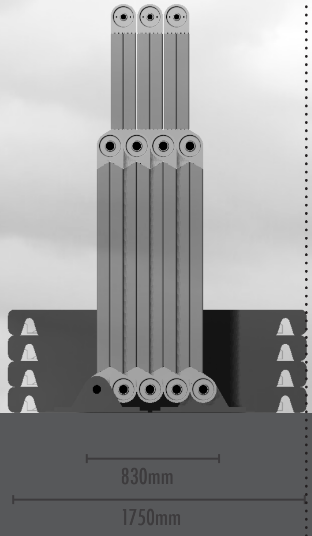
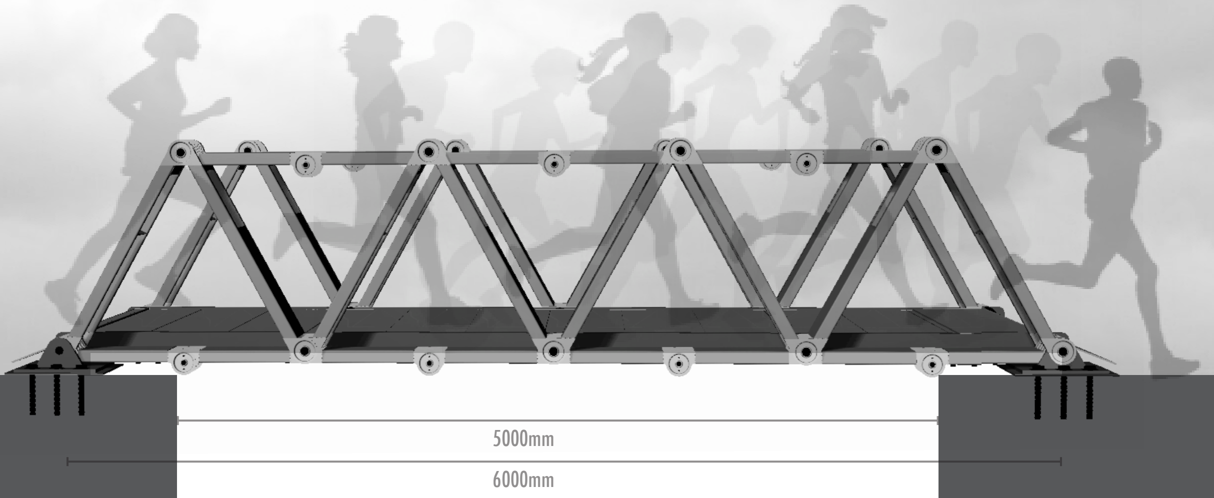


Figure 5.20 | 3D and view of the ramp, scale 1:20

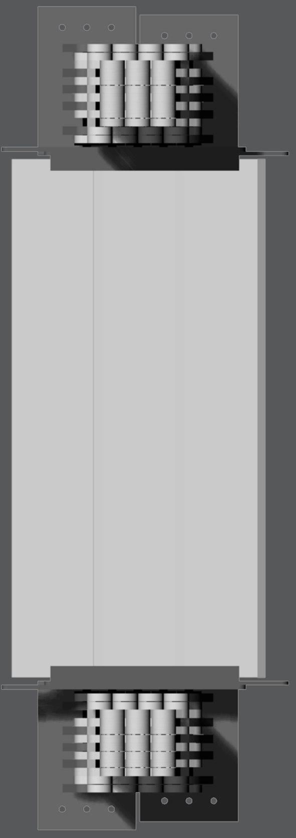
DeMoLi6 application



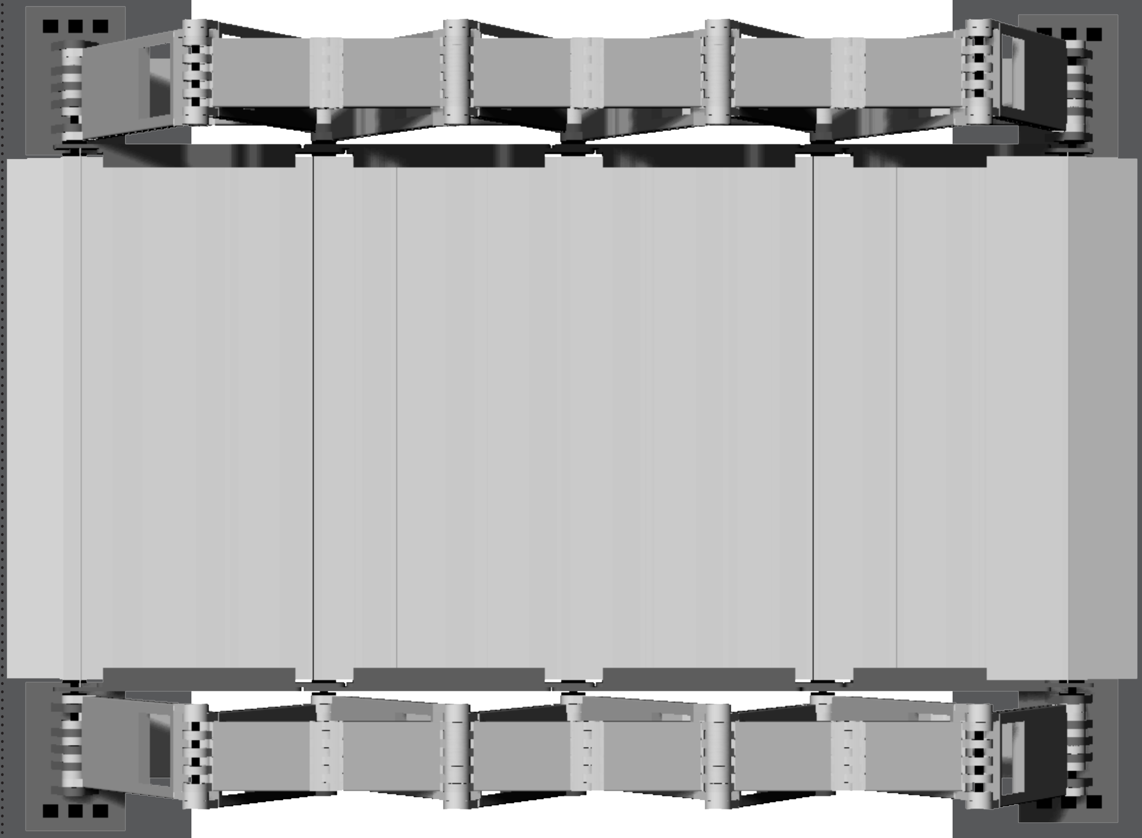
Compacted Configuration, Side View



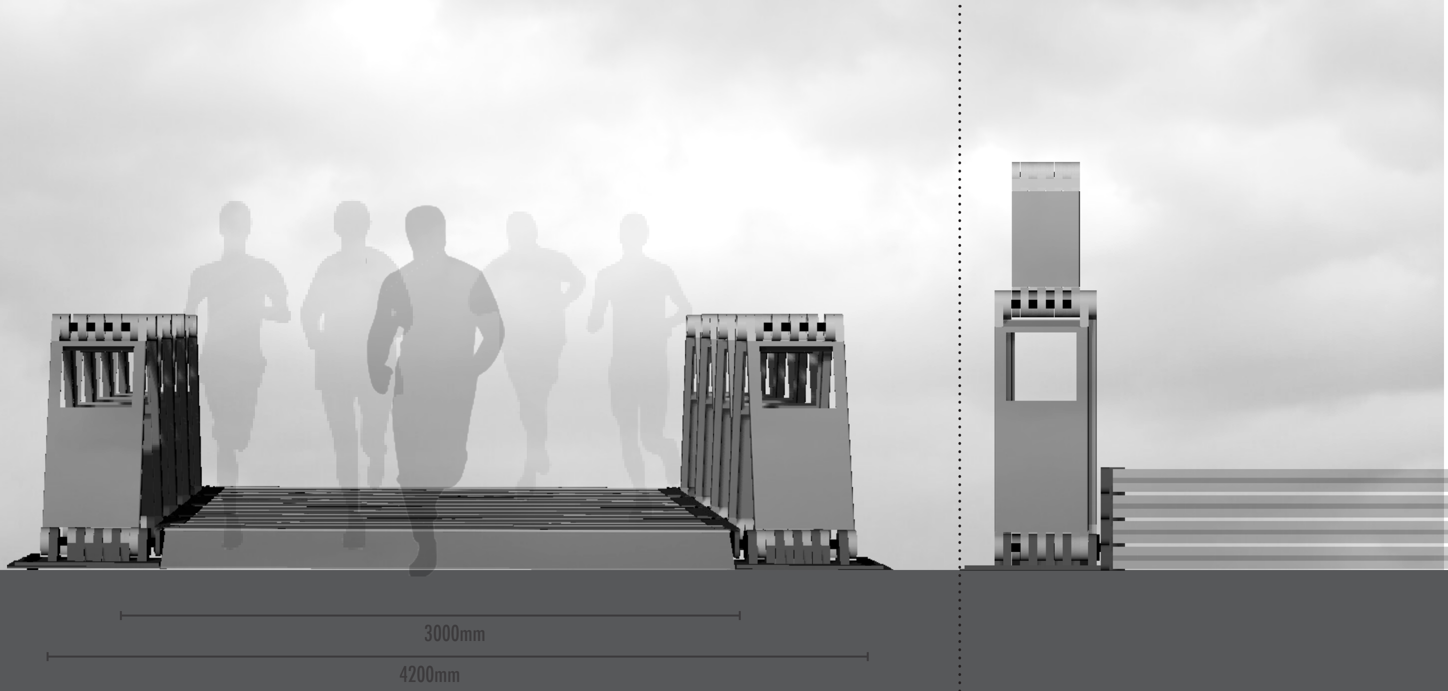
Side View



Compacted Configuration, Plan



Plan



Front View

Compacted Configuration, Front View

Figure3.21 | Architectural Drawings for DeMoLi6

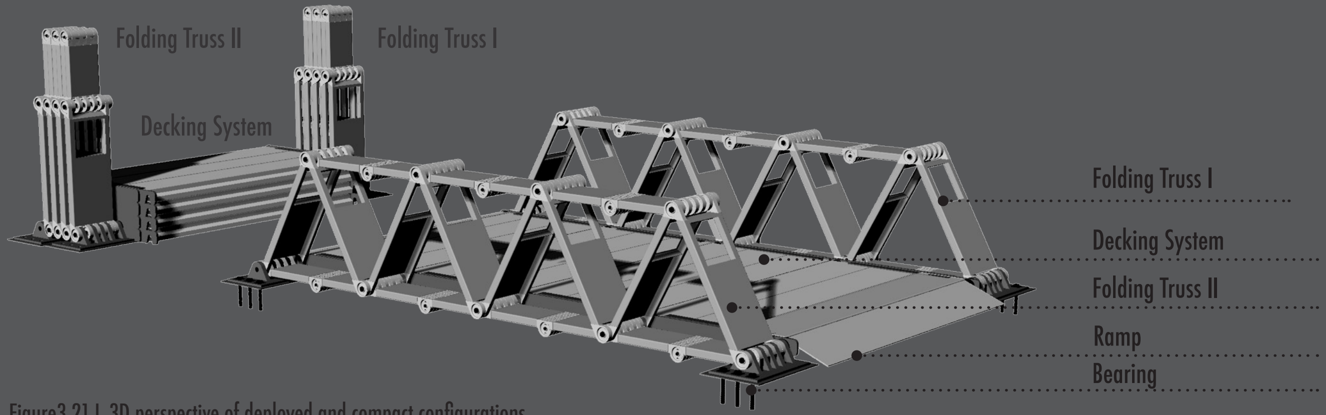


Figure3.21 | 3D perspective of deployed and compact configurations

6.

Implementation

Implementation phase refers to the final process of moving the solution from development status to production status. During this final phase, the project takes its final, realistic shape.
For the purposes of DeMoLi project, implementation is related to a series of steps from fabrication, assembly and transportation unlit the final installation and the possibility of relocation. All these are presented as a sequence of plans, which are synonymous with "implementation".
Finally, this phase involves the visualization of the project results through mock-ups in different scales from 1:50 to 1:2.

When the design process is completed, the next step is to create implementation plans that describe how fabrication, assembly, transportation and installation are done. Implementation Phase refers to these plans and analytically to [Figure 6.1]:

1. Fabrication Plan: How to fabricate the parts,
2. Assembly Plan: How to connect the parts into a final line assembly,
3. Transportation Plan: How to transport all the bridge's elements, and
4. Installation Plan: How the installation process is realized on-site.

6.1 Fabrication Plan

This plan describes how all the involved components of the bridge are fabricated. Constructing for lightness and economy is a delicate matter of harmony between material, shape and production process. Optimum material distribution can be combined with the preferable fabrication constraints in order to improve the efficiency of the structure. Furthermore, the load capacity of a structure can be increased without increasing the amount of material, by choosing an adequate form and the appropriate material- fabrication process. This has special importance when designing deployable structures, because increasing the carried-capacity by adding material will make the movable joints used more expensive that they already are, and will increase the weight of all components, therefore the overall weight of the structure, reducing its efficiency and transportability. [6.1]
As it was explained during the Design Verification Phase, the selected materials for both truss and decking system are aluminum alloys, and the manufacturing processes are casting and extrusion. Cast aluminum is used for the hinged connections, while extruded profiles form the leaves and the deck panels. The next

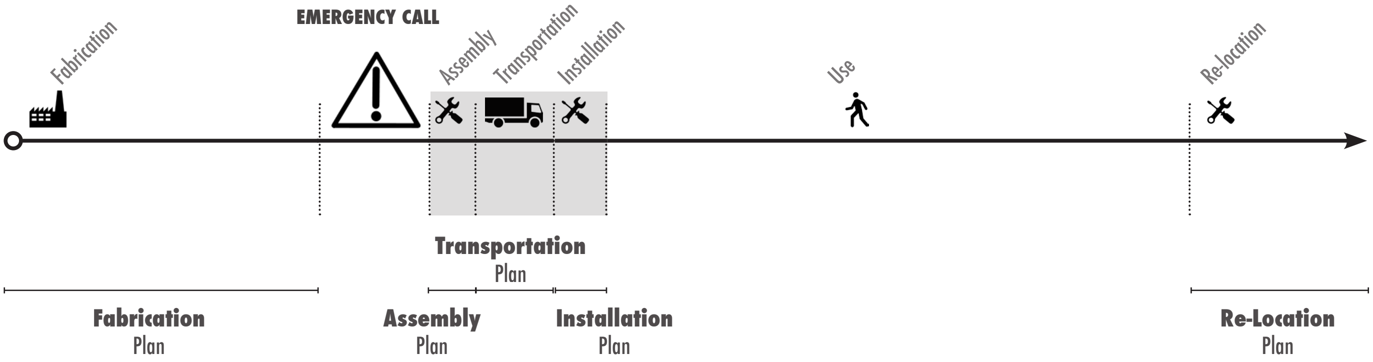


Figure 6.1 | Scheme showing the whole process from fabrication, assembly, transportation and installation until relocation

parts describe these two fabrication techniques explaining how they are applied to the proposal design. [Figure 6.2]

6.1.1 Cast Aluminum

At the initial steps, hinges were designed as solid forms satisfying their main use. In next steps they were redesigned with less material and processing a much more efficient solution. Comparing the weight of the first and last designs, the benefits for the second ones are obvious saving approximately 25% weight. In order to reach the fluid improved form, all the hinged connections are casted achieving lighter and more efficient components by applying material, where it is need to deal with stresses and by leaving it out where its contribution has no value. The results are interpreted into an optimized design.

Aluminum can be cast into an infinite variety of solid, uniquely shapes by pouring the molten metal into a mold. As the aluminum cools and hardens, it takes the shape of the mold.

The three most common casting methods are die casting, sand casting and investment casting.

The die casting process forces molten aluminum into a steel die (mold) under pressure. The mold cavity is created using two hardened tool steel dies, which have been machined into shape and work similarly to an injection mold during the process. The dies are permanent, allowing this technique to be used for high-volume production. The parts from die casting are precisely formed, requiring a minimum of machining and finishing. However, its main disadvantage is related to the high initial cost due to the fact that large capital investment is required to set up a pressure die casting process, as the die casting machines and tooling costs are very expensive. Furthermore, there are shape limitations due to the fact that the die is permanent and therefore it has to be able to detached from the casting element without destroyed.

The most versatile method for producing aluminum products is sand casting. In sand casting, re-usable, permanent patterns are used to make the sand molds. The process starts with a pattern that is a replica of the finished casting[1]. Then this pattern is pressed into a fine sand mixture to form the mold into which the aluminum is poured. The preparation and the bonding of this sand mold are the critical steps and very often are the rate-controlling steps of this process. As compared to die casting, sand casting is a slow process but usually more economical for small quantities or when a very large casting is required.

Investment casting is an industrial process based on and also called lost-wax cast-

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[1] The pattern is slightly larger than the part to be made, to allow for aluminum shrinkage during solidification and cooling.

ing. The wax pattern, which is normally produced with injection molding, is coated with a refractory ceramic material. Once the ceramic material is hardened its internal geometry takes the shape of the casting. The wax is melted out and molten metal is poured into the cavity where the wax pattern was. The metal solidifies within the ceramic mold and when the aluminum is solidified, the ceramic mold is broken and the casting part is ready with a good surface finish[2].

Although, investment casting is a complicated and relatively expensive process it allows the casting of extremely complex and intricate shapes with internal voids. Therefore, this is the selected casting method for the hinged parts of DeMoLi Bridge.

Facilitating the process, multiple patterns are created and then assembled into one complex pattern by attaching to a sprue, with the result known as a pattern cluster or tree. Specifically, six hinged patterns of the horizontal element are assembled into one tree and in another tree, 24 patterns of the diagonal elements. The trees are shown in Figure 6.2 [fabrication techniques].

Nowadays, there are a lot of improvements in investment casting method. One of them is the use of Fused Deposition Modeling (FDM). FDM provides an alternative method for producing investment casting patterns that can provide high time and cost savings. FDM technology is an additive manufacturing process that builds plastic parts layer by layer, using data from CAD files. Since FDM is an additive process, the pattern can be as complex as needed without any impact on cost. By applying this method the wax pattern can be replaced by PLA pattern, converting the lost-wax technique to lost- PLA one.

6.1.2 Extruded Aluminum

The most cost-effective way to manufacture constant cross- section aluminum profiles is extrusion. This process is highly automated, uses low-cost forms of raw material and represents a relatively simple way of producing complex sections. Taking the unique benefits of aluminum, in combination with the extrusion process a cost-effective and lightweight product with optimal functionality is produced.

The extrusion process itself is easy to be explained[3]. A preheated billet of aluminum is positioned in an also preheated container. Under the forces of the stem, the material begins to flow through the die and acquires the form defined by it. So, the shape- openings of the die determine the shape of the extruded aluminum. The die is in reality the most important device in this process. In its simplest form, it is a disc with an opening corresponding to the outer contour of the shape of the section. The extrusion dies are made from high-strength, heat-resistant tool steel.

Since the die changing is an easy process, most engineers design their own cross-sectional form optimally adapting them to the special requirements of each application. This brings considerable advantages like the cost, the weight reduction, etc. In this way, the section is given its optimized form in terms of functionality and often machining costs are also saved. This individualism due to the special process of extruding has given aluminum tremendous advantages but also has

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[2] Analytically, the process steps of investment casting include the following: pattern creation (wax patterns are typically injection molded into a metal die and are formed as one piece), mold creation (the pattern is dipped into a slurry of fine ceramic particles, coated with more coarse particles, and then dried to form a ceramic shell around the patterns and gating system), melting (the shell is then placed into an oven and the pattern is melted out leaving a hollow ceramic shell that acts as a one-piece mold), pouring (the molten metal is poured into the gating system of the mold, filling the mold cavity), cooling (after the mold has been filled, the molten metal is allowed to cool and solidify into the shape of the final casting), casting removal (after the molten metal has been cooled, the mold can be broken and the casting removed) and finally finishing.

[3] In principle, extrusion functions like squeezing paste out of a tube. [6.2]

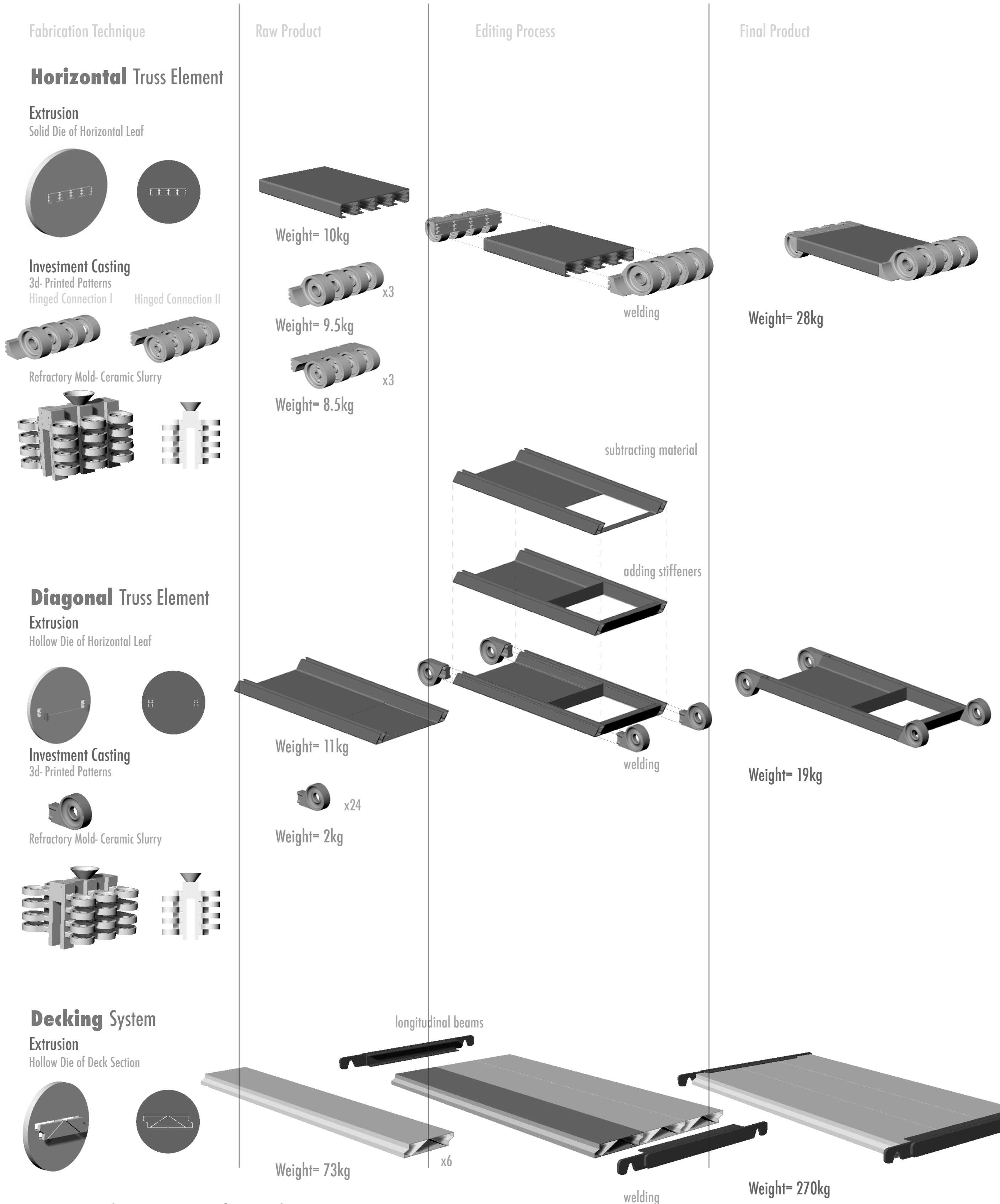

Figure 6.2 | Fabrication Processes of DeMoLi elements

			Trussed Members (x2)								Decking System		
			Horizontals		Diagonals		Hinged Connection I		Hinged Connection II		Panels		
DeMoLi (length)	Span- x (m)	Number of module (N)	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)	Total Weight (kg)
DeMoL(6)	x=<5.00	4	14	378	8	151.2	9	70.29	7	21.868	4	1080	**2323**
DeMoLi(7.5)	5.00<x=<6.50	5	18	486	10	189	11	85.91	9	28.116	5	1350	**2928**
DeMoLi(9)	6.50<x=<8.00	6	22	594	12	226.8	13	101.53	11	34.364	6	1620	**3533**
DeMoLi(10.5)	8.00<x=<9.50	7	26	702	14	264.6	15	117.15	13	40.612	7	1890	**4139**
DeMoLi(12)	9.50<x=<11.00	8	30	810	16	302.4	17	132.77	15	46.86	8	2160	**4744**
DeMoLi(13.5)	11.00<x=<12.50	9	34	918	18	340.2	19	148.39	17	53.108	9	2430	**5349**
DeMoLi(15)	12.50<x=<14.00	10	38	1026	20	378	21	164.01	19	59.356	10	2700	**5955**
DeMoLi(16.5)	14.00<x=<15.50	11	42	1134	22	415.8	23	179.63	21	65.604	11	2970	**6560**
DeMoLi(18)	15.50<x=<17.00	12	46	1242	24	453.6	25	195.25	23	71.852	12	3240	**7165**
DeMoLi(19.5)	17.00<x=<18.50	13	50	1350	26	491.4	27	210.87	25	78.1	13	3510	**7771**
DeMoLi(21)	18.50<x=<20.00	14	54	1458	28	529.2	29	226.49	27	84.348	14	3780	**8376**

Figure 6.3| Characteristic values for all the DeMoLi solutions

certain limitation mainly related to the possible dimensions of the cross section, the length and the thickness. Generally, the wall thickness can vary from 1.5 to 100mm and the maximum overall dimensions have to be no longer than 600mm [6.2], which are covering the design requirements of DeMoLi Bridge solution (the maximum is 550mm for the diagonal leaves). In theory, there is no limit to the length of the components because the sections are produced continuously.

Modular systems are developed to overcome the limited dimensional possibilities with extruded cross section. It is therefore possible to fabricate large elements by combining smaller ones.

Extrusion requires comparatively elaborate and expensive tooling, and setting up the plant is very time-consuming, all of which means that custom sections are worthwhile only for large qualities (usually at least 1000 production meters) [6.2].

The whole manufacturing and production process starts from the design. It is here that the extrusion takes shape and features are built in to reduce weight, simplify assembly, add functionality and minimize finishing costs. There are two basic classes of profile:

A. Solid, which creates solid extrusions without cavities by using a flat, disc-shaped die, and

B. Hollow, which create hollow extrusions with cavities. In hollow dies, the mandrel (the part that shapes the cavity in the profile), is supported by a bridge, porthole or spider dies.

Solid profiles reduce die costs and are easier to produce, since they facilitate the production by making it simpler to extrude.

In Figure 6.2 [fabrication techniques] the three types of dies, for horizontal and diagonal leaves and the deck extrusion are illustrated. Horizontal leaves are solid profiles consists of four open voids and they have 555mm length. The diagonal elements are hollow, 1190m long profiles. Finally, decking panels in proposal design is a modular three-hollow profile. Each deck panel consists of three extruded profiles of 500mm each welded together in order to form the desirable panel, with width of 1500mm. The hollow section of each extrusion is necessary in order to form a truss-like deck panel.

After the creation of all the parts, both casted and extruded, the finishing and modifying are followed. Finally, they are jointed together forming the final products. The joining method that is applied between them (hinges and leaves or panel and beams) is welding. Thus the final products (horizontal and diagonal elements and decking panels) behave as uniform, completed elements.

DeMoLi "x"

GAP from 5.00-20.00 (m)	x
TRUSS	
Number of Horizontal Elements	#VALUE!
Weight of Horizontal Elements (kg)	#VALUE!
Number of Diagonal Elements	#VALUE!
Weight of DiagonalElements (kg)	#VALUE!
Number of Pins, Hinged Connection I	#VALUE!
Weight of Pins, Hinged Connection I (kg)	#VALUE!
Number of Pins, Hinged Connection II	#VALUE!
Weight of Pins, Hinged Connection II (kg)	#VALUE!
Total Weight of Truss (kg)	#VALUE!
Total Weight of Both Trusses (kg)	#VALUE!
Total Volume for Transportation (m^3)	#VALUE!
DECK	
Number of Deck Sections	#VALUE!
Total Weight of Deck (kg)	#VALUE!
Total Volume for Transportation (m^3)	#VALUE!
GENERAL	
Number of Modules (triangles)	#VALUE!
Length (m)	#VALUE!
Width (m)	3
Total Volume for Transportation (	#VALUE!
Pedestrian load- 5MPa (kN)	#VALUE!
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**#VALUE!**

DeMoLi 6

GAP from 5.00-20.00 (m)	5.00
TRUSS	
Number of Horizontal Elements	14
Weight of Horizontal Elements (kg)	378
Number of Diagonal Elements	8
Weight of DiagonalElements (kg)	151.2
Number of Pins, Hinged Connection I	9
Weight of Pins, Hinged Connection I (kg)	70.29
Number of Pins, Hinged Connection II	7
Weight of Pins, Hinged Connection II (kg)	21.868
Total Weight of Truss (kg)	621.358
Total Weight of Both Trusses (kg)	1242.716
Total Volume for Transportation (m^3)	0.76
DECK	
Number of Deck Sections	4
Total Weight of Deck (kg)	1080
Total Volume for Transportation (m^3)	41.4
GENERAL	
Number of Modules (triangles)	4
Length (m)	6
Width (m)	3
Total Volume for Transportation (	42.16
Pedestrian load- 5MPa (kN)	58
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**2323**

DeMoLi 21

GAP from 5.00-20.00 (m)	20.00
TRUSS	
Number of Horizontal Elements	54
Weight of Horizontal Elements (kg)	1458
Number of Diagonal Elements	28
Weight of DiagonalElements (kg)	529.2
Number of Pins, Hinged Connection I	29
Weight of Pins, Hinged Connection I (kg)	226.49
Number of Pins, Hinged Connection II	27
Weight of Pins, Hinged Connection II (kg)	84.348
Total Weight of Truss (kg)	2298.038
Total Weight of Both Trusses (kg)	4596.076
Total Volume for Transportation (m^3)	2.66
DECK	
Number of Deck Sections	14
Total Weight of Deck (kg)	3780
Total Volume for Transportation (m^3)	144.9
GENERAL	
Number of Modules (triangles)	14
Length (m)	21
Width (m)	3
Total Volume for Transportation (	147.56
Pedestrian load- 5MPa (kN)	202
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**8376**

DeMoLi 9

GAP from 5.00-20.00 (m)	8.00
TRUSS	
Number of Horizontal Elements	22
Weight of Horizontal Elements (kg)	594
Number of Diagonal Elements	12
Weight of DiagonalElements (kg)	226.8
Number of Pins, Hinged Connection I	13
Weight of Pins, Hinged Connection I (kg)	101.53
Number of Pins, Hinged Connection II	11
Weight of Pins, Hinged Connection II (kg)	34.364
Total Weight of Truss (kg)	956.694
Total Weight of Both Trusses (kg)	1913.388
Total Volume for Transportation (m^3)	1.14
DECK	
Number of Deck Sections	6
Total Weight of Deck (kg)	1620
Total Volume for Transportation (m^3)	62.1
GENERAL	
Number of Modules (triangles)	6
Length (m)	9
Width (m)	3
Total Volume for Transportation (	63.24
Pedestrian load- 5MPa (kN)	86
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**3533**

DeMoLi 12

GAP from 5.00-20.00 (m)	11.00
TRUSS	
Number of Horizontal Elements	30
Weight of Horizontal Elements (kg)	810
Number of Diagonal Elements	16
Weight of DiagonalElements (kg)	302.4
Number of Pins, Hinged Connection I	17
Weight of Pins, Hinged Connection I (kg)	132.77
Number of Pins, Hinged Connection II	15
Weight of Pins, Hinged Connection II (kg)	46.86
Total Weight of Truss (kg)	1292.03
Total Weight of Both Trusses (kg)	2584.06
Total Volume for Transportation (m^3)	1.52
DECK	
Number of Deck Sections	8
Total Weight of Deck (kg)	2160
Total Volume for Transportation (m^3)	82.8
GENERAL	
Number of Modules (triangles)	8
Length (m)	12
Width (m)	3
Total Volume for Transportation (	84.32
Pedestrian load- 5MPa (kN)	115
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**4744**

DeMoLi 15

GAP from 5.00-20.00 (m)	14.00
TRUSS	
Number of Horizontal Elements	38
Weight of Horizontal Elements (kg)	1026
Number of Diagonal Elements	20
Weight of DiagonalElements (kg)	378
Number of Pins, Hinged Connection I	21
Weight of Pins, Hinged Connection I (kg)	164.01
Number of Pins, Hinged Connection II	19
Weight of Pins, Hinged Connection II (kg)	59.356
Total Weight of Truss (kg)	1627.366
Total Weight of Both Trusses (kg)	3254.732
Total Volume for Transportation (m^3)	1.9
DECK	
Number of Deck Sections	10
Total Weight of Deck (kg)	2700
Total Volume for Transportation (m^3)	103.5
GENERAL	
Number of Modules (triangles)	10
Length (m)	15
Width (m)	3
Total Volume for Transportation (	105.4
Pedestrian load- 5MPa (kN)	144
Vehicle load- 36tons (kN)	360
Total Weght (kg)	**5955**

Figure 6.4 | Technical Specifications according an algorithm for DeMoLi6, DeMoLi 9, DeMoLi12, DeMoLi12 and DeMoLi21

6.2 Assembly Plan

Based on the fabrication plan, all the elements, of truss and deck, are pre-constructed and they are ready to be assembled in any emergency call.

In order to make the assembly process easier, especially under the panic of an emergency situation, beyond the list of the basic characteristics of each DeMoLi [Figure 6.3], an algorithm through Excel is constructed. The only input data is the gap's length and according to this, several parameters like the number of elements that they have to be assembled, the total weight, the volume in compacted configuration, etc. are defined. [Figure 6.4]

After the emergency call, the number of elements, according to the specific situation are assembled and packed with the sequence as that is showed in Figure 6.5.

The assembling process takes place in the following steps:

Firstly, the defined number of components, according to the specific situation, as well as the bearings are assembled by positioning the rotational pins. Then, both trusses are folded and locked in their compacted configuration. Simultaneously to the above process, the defined number of deck panels is stacked on the top to each other on a transportation pallet.

Due to the fact that the parts are lightweight, more specifically the horizontal ones are 28kg and the diagonals 19kg, during the assembly they can be carried manually from one or two people.

6.3 Transportation Plan

The general sizes of all the members are being determined by transportation constraints from the fabrication to bridge site.

For the transportation of the structure a *Truck Mounted Crane* is needed, which it is also used for lifting, loading and unloading. The parts of the bridge are fitted in, it as it shown in Figure 6.6. They folds up into a stack of hinged segments that can be easily handled by forklift, allowing quick loading of an entire bridge system into a shipping container for transportation.

Both trusses are transported in their locked- compacted configuration, while the panels are stack on the top to each other. The final volume in compacted configuration for transportation purposes for both truss and deck is estimated only 0.6m^3/m:

DeMoLi 6: 3.76m^3
DeMoLi 9: 5.40m^3
DeMoLi 12: 7.56m^3
DeMoLi 15: 9.00m^3
DeMoLi 21: 12.66m^3

Moreover, its lightweight construction minimizes the associated transportation resources. The weight of both trusses is 180kg/m, including all the extra elements, such as pins, bearing, etc., and of one deck panel is 270kg. The total weigh is estimated 400kg/m:

DeMoLi 6: 2323kg
DeMoLi 9: 3533kg
DeMoLi 12: 4744kg
DeMoLi 15: 5955kg
DeMoLi 21: 8376kg

The maximum required dimensions that are needed for the cargo platform are 1750mm (width), 2600mm (height) and 5860mm (length). Although the width and height of the transportation package are standard, the length varies from 4300-5860mm from every different DeMoLi size. The required truck in each case has to have these dimensions as the minimum.

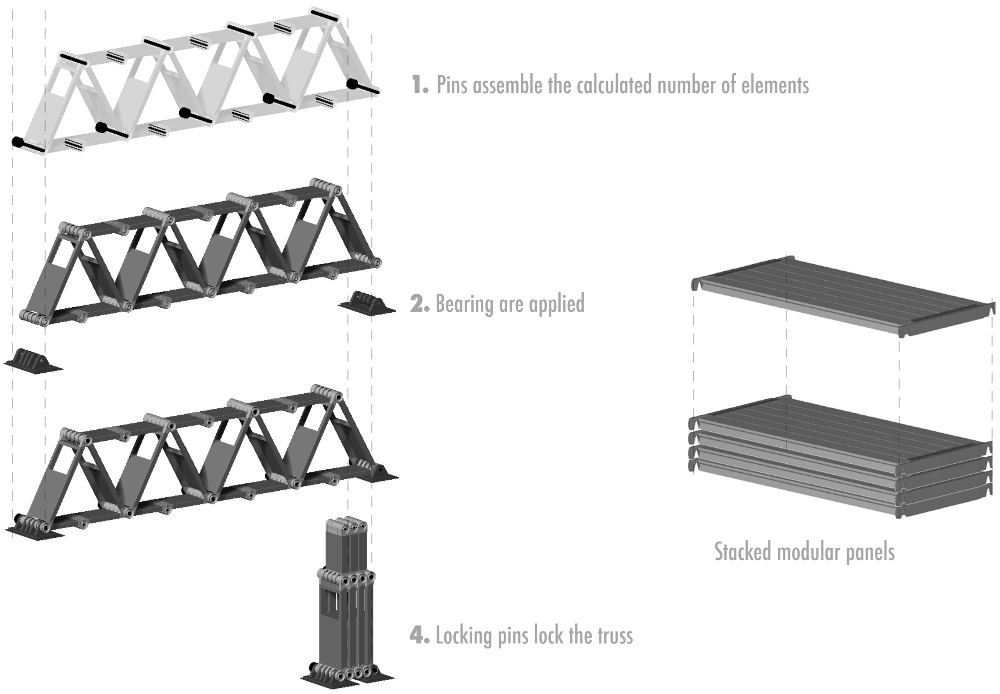

Figure 6.5 | Assembly and packaging processes for both truss and deck

Packaging Height: max 2600mm (truss)
Packaging Width: max 1750mm (deck)
Packaging Length: max 5860mm (truss + deck)

maximum volume: 2600 x 1750 x 5860 mm

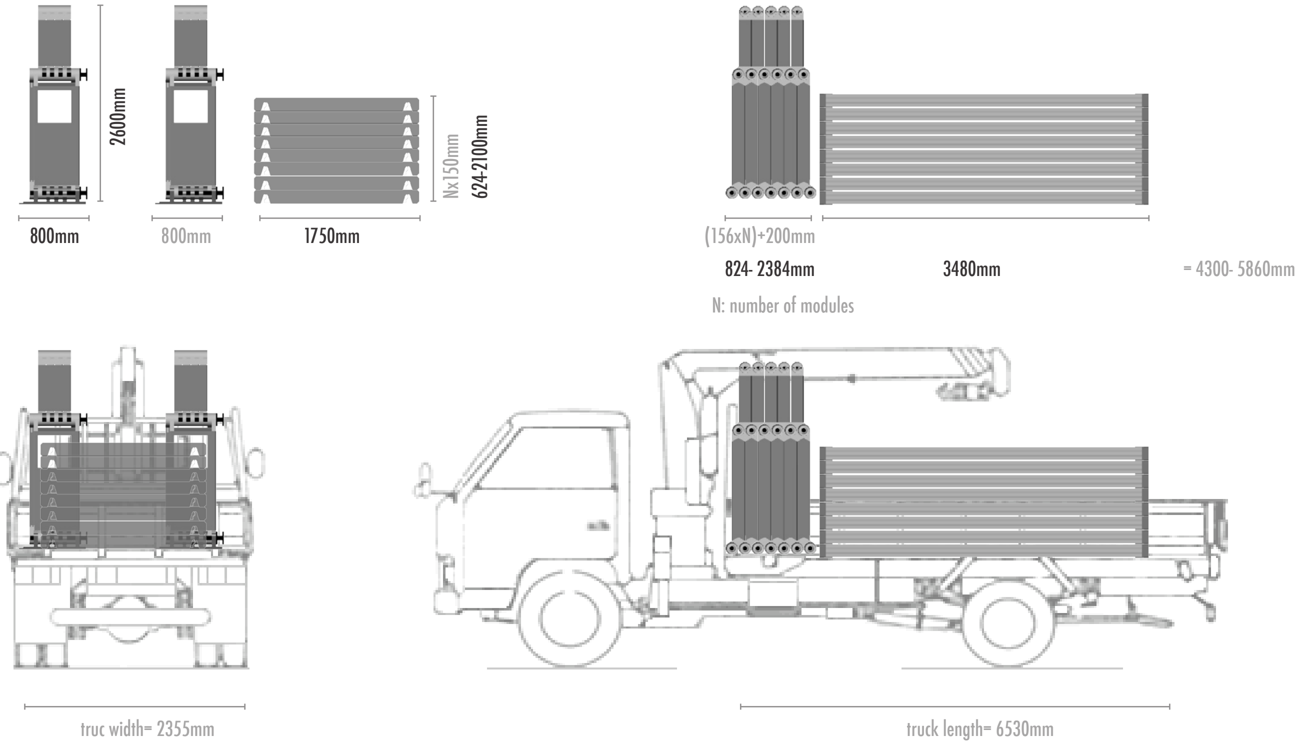

Figure 6.6 | Logistic process with the general dimensions of a truck mounted crane and the DeMoLi9 Bridge

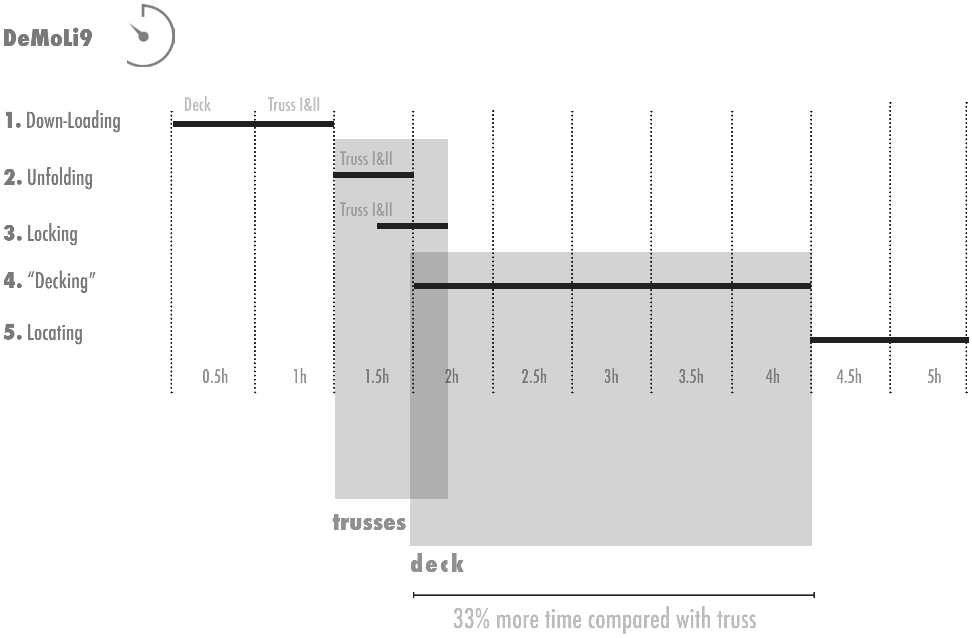

Figure 6.8 | Time-line with estimated erection time for DeMoLi9

The used crane is chosen according to its loading capacity and the weight of the structure. Consequently, regarding each DeMoLi's length, different sizes cranes are used. The carrying capacity of the crane can varies from 3tonnes to 9tonnes.

6.4 Installation Plan

The bridge can be installed in a matter of hours by a small crew using common tools.

As we can see in Figure 6.7 and the application of DeMoLi9 Bridge, the installation process involves the following steps:

Firstly, the equipment is unloaded form the truck by the crane. In total, there are three packages that they have to unload. These are the two trusses and the deck panels, which are wrapped together. Due to the compacted form of the trusses, the unloading is realized easier and faster. Then, the two folding trusses are located in their final, precise distance in order to receive the decking panels and they are deployed. The following step is the locking process of the upper hinged connections II by inserting the two locking pins (pounding them). Afterwards, the deck panels are positioned by the crane one by one. Finally, the whole structure is located to the gap, it is anchored on the shore through the bearing and the ramps are open to facilitate the movement.

Since there is not any more the need of the bridge, it is un-installed following exactly the opposite of installation process and the bridge is ready to be used in the next emergency call. Maintenance and replacement of damaged parts or general modification after the use are feasible and also reasonably simple, due to the modular character of the structure.

In ideal conditions, a DeMoLi9 can be assembled in five hours with a team of 4 workers and the truck-mounted crane that is used for the transportation.

From the time-line of Figure 6.8, it is obvious that the most cost-consuming process is the location of the deck. This is the only time that varies for the different DeMoLi applications. In general, it is estimated that the time range from 3,5 to 7 hours.

In some cases, where the crane is not an option, there is an extra installation plan. In plan B, all the process is manually and the final locating is achieved though the old "cantilever launching" that was invented in Bailey bridge. This method needs

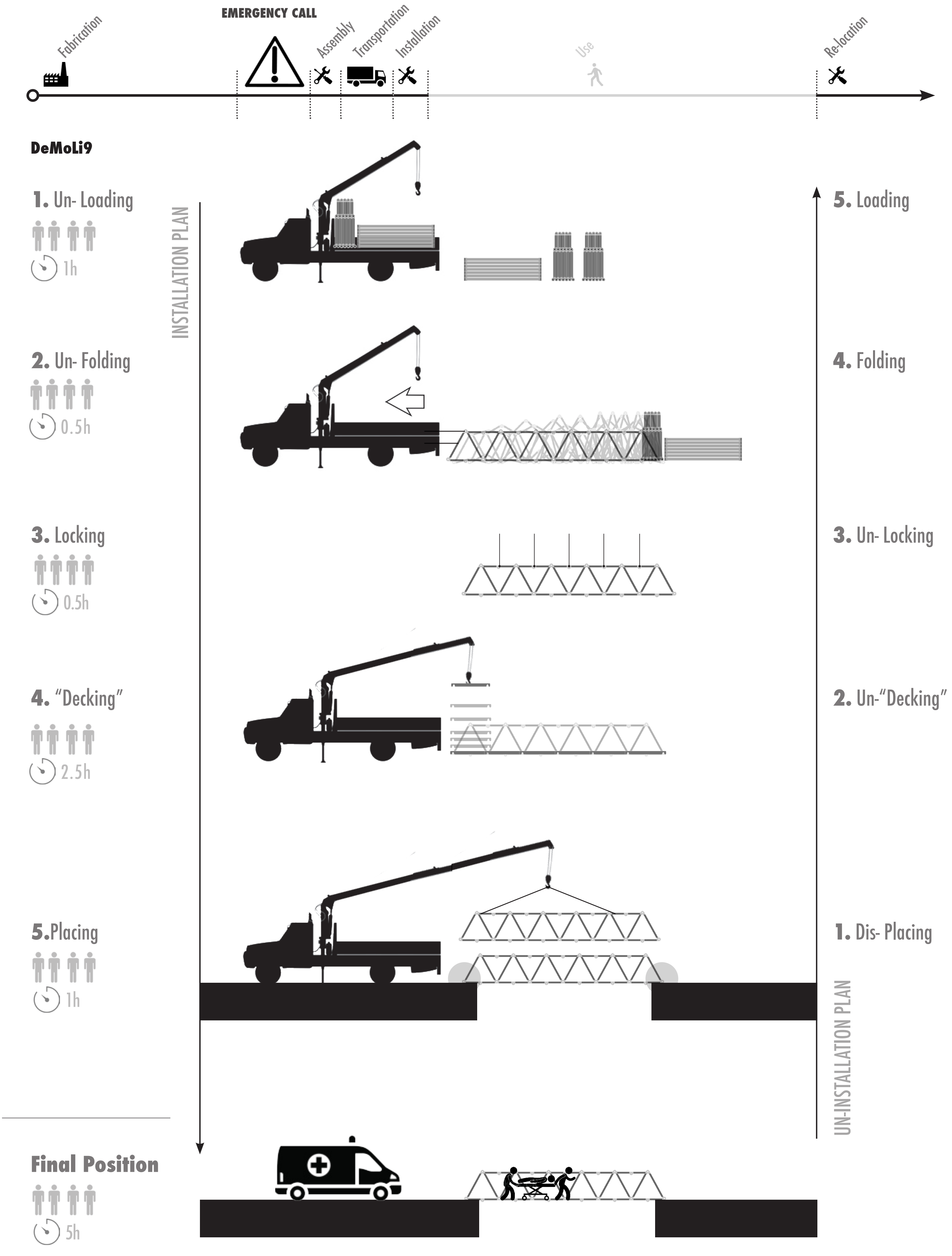

Figure 6.7 | Installation Plan of DeMoLi9

Figure 6.9 | Mock-ups in scale 1:20 of the Conceptual Designs
Both of the concepts form truss structures made of panels with movable connections. The Deployable System of Concept I use telescopic diagonal elements. In order to reduce complexity of the initial concept, the Concept Design II was invested, where there are no extra mechanisms (telescopic) and less complicate movable connections.

Figure 6.10 | Mock-up in scale 1:5 made of cardboard
Although this mock-up had a lot of weak points, it was helpful for the very first visualization of the proposal design. It was the starting point for aspects such as the detailing of hinged connections and a way to form a really compact solution.

Figure 6.11 | Mock-ups in scale 1:5 made of laser cut wood
With this mock-up the general concept of the folding mechanism is easy understandable. Stripes in a specified shape were cut be a laser machine and then glued together to form the panels.
The hinged connections with the knuckles and notches are clearly visualized. In addition, the compact shape due to the bigger width of the diagonal members is also visible.
One important missing point is the locking system and therefore the structure behaves like a mechanism.

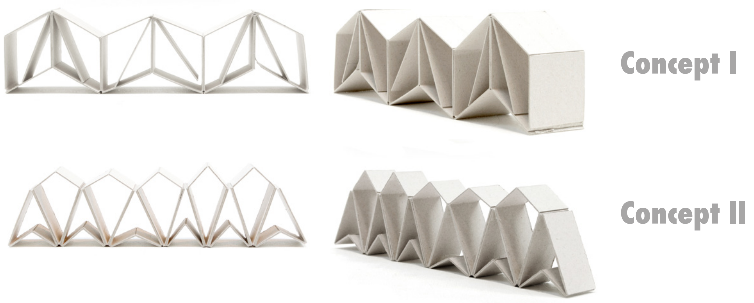

Figure 6.9 | Mock-ups in scale 1:20 of the Conceptual Design

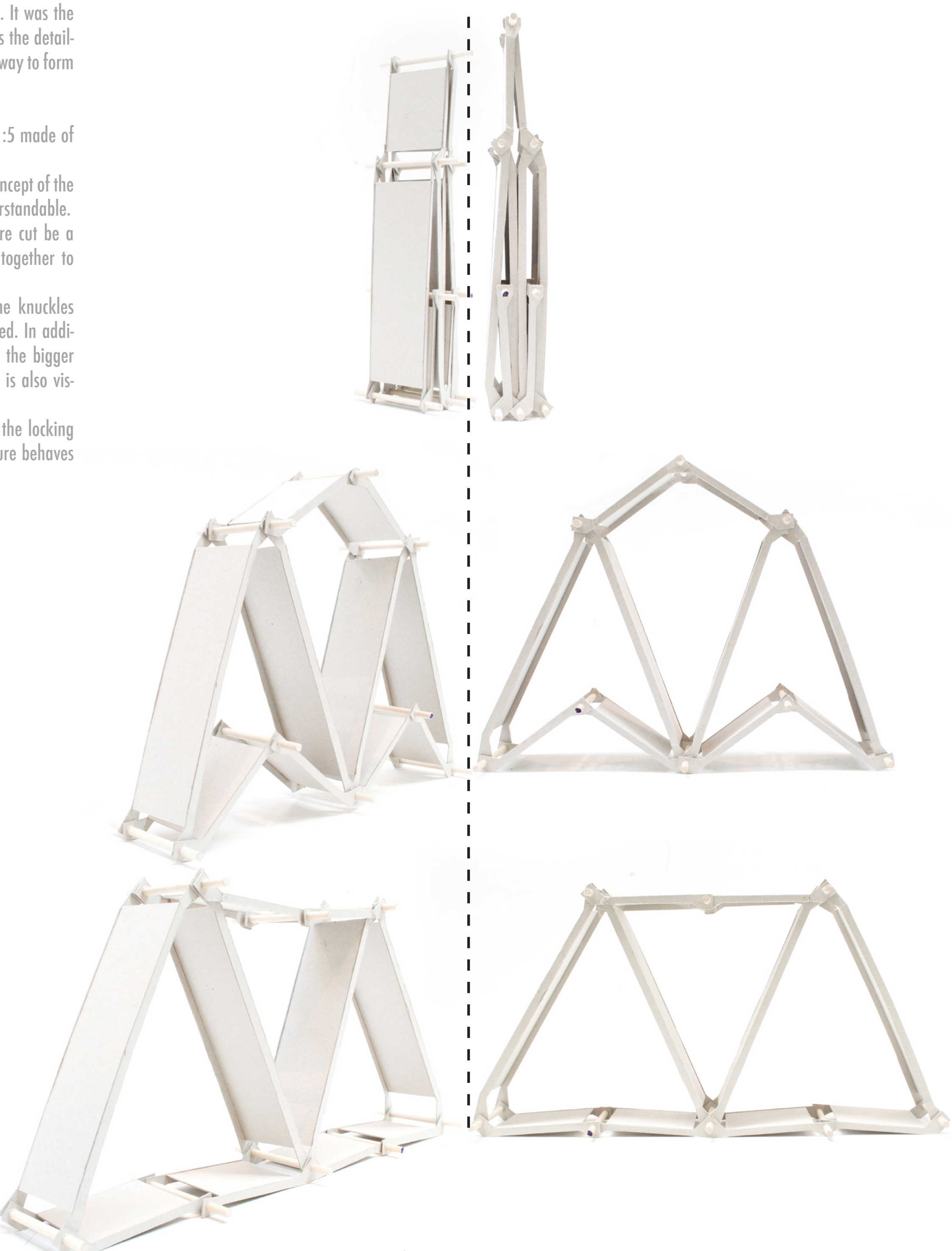

Figure 6.10 | Mock-up in scale 1:5 made of cardboard

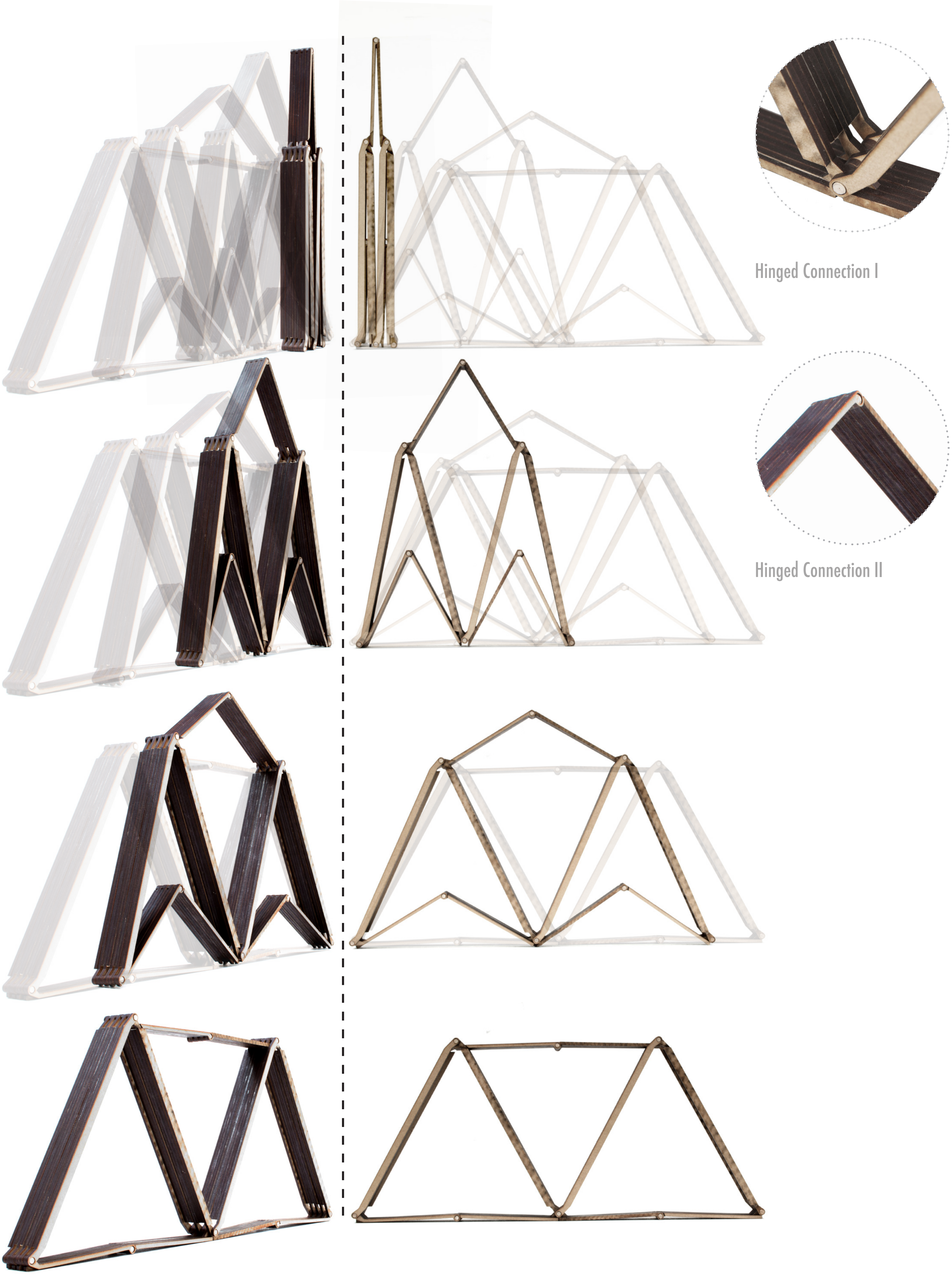

Figure 6.11 | Mock-up in scale 1:5 made of laser cut wood

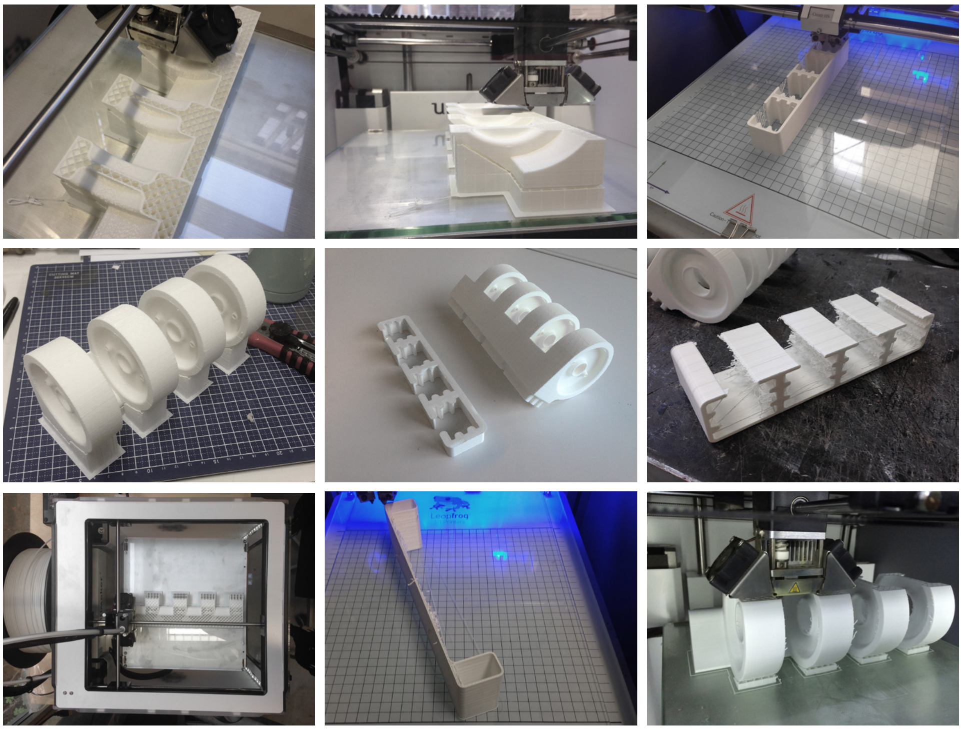

Figure 6.12 | 3d- printing process

more time and effort but the final result is the same. The maximum dimensions of constructed component are 3.00m long, 1.50m width and it weights 270kg. Therefore, it can be easily handled by a crew of 6.

6.5 Development through Mock-ups

During the whole process, physical models in diverse scales have been made, starting from scale to 1:20, then to 1:5 and finally to 1:2. All of them were focused on the truss and its folding capacity.

The models were constructed mainly for two purposes. The first one was to check the folding and deploying sequences of the system and the second to determinate and visualize these two processes.

The first experimental tests were made out of folding cardboard in scale 1:20 [Figure 6.8]. All the movable joints are the connecting lines between the different panels.

The second scaled models of the truss were constructed in scale 1:5. [Figure 6.9 and 6.10] Specifically, the fabricated truss consists of three building blocks (three triangles) with total length of 30cm.

Finally, two nodes of hinged connection I and II were fabricated. Although these mock-ups were planned to made of real material and fabrication method (aluminum and sand casting), due to the limited budget, the process was limited to the generation of the parts out of PLA proceed with FDM printers [Figure 6.12]. These 3d-printing parts can be used in a further development as the patterns for the casting. The final result of the mock-up is shown in Figure 6.13. It consists of the two 3d-printing nodes [Figure 6.14 and 6.15], which are connected with the MDF elements creating one triangular, foldable building block. Specifically, each node is demountable, with the parts that in reality are casted and extruded to be printed separate. The extrusion sections are visualized in a more complex shape than the proposal solution, however, since this made the assembly process more difficult, in the proposal solution the section is presented in a more rational shape.

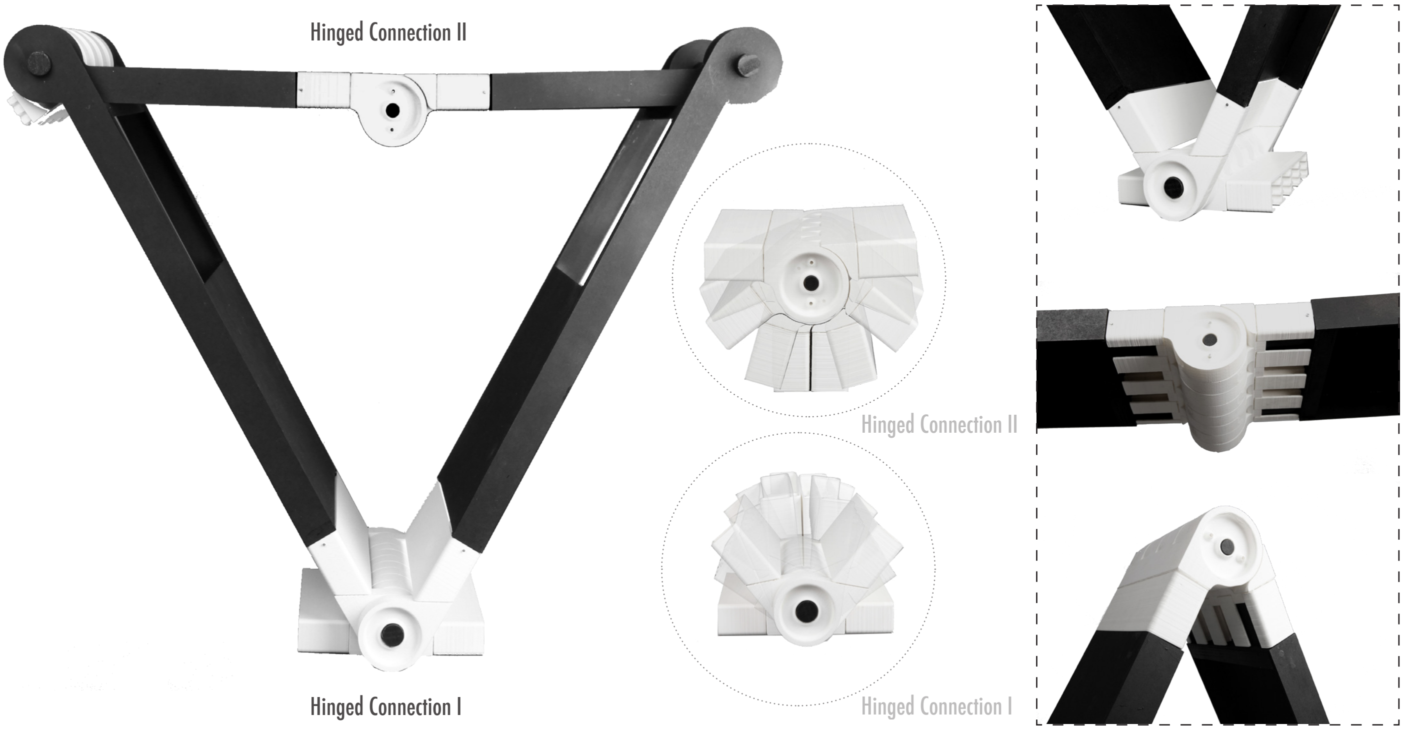

Figure 6.13 | The final Mock-up, scale 1:2

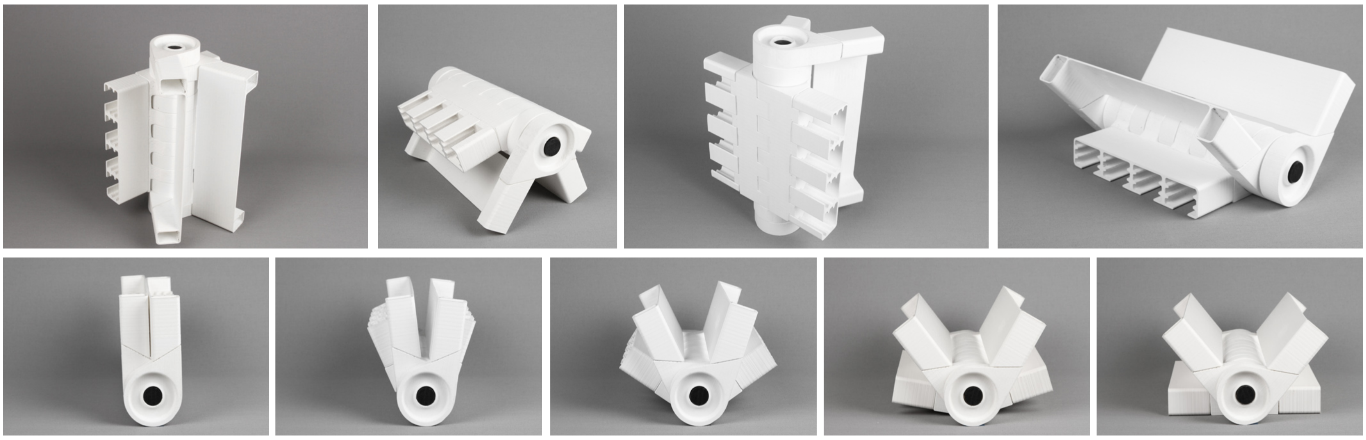

Figure 6.14 | Hinged Connection I made of PLA proceed with FDM printers, scale 1:2

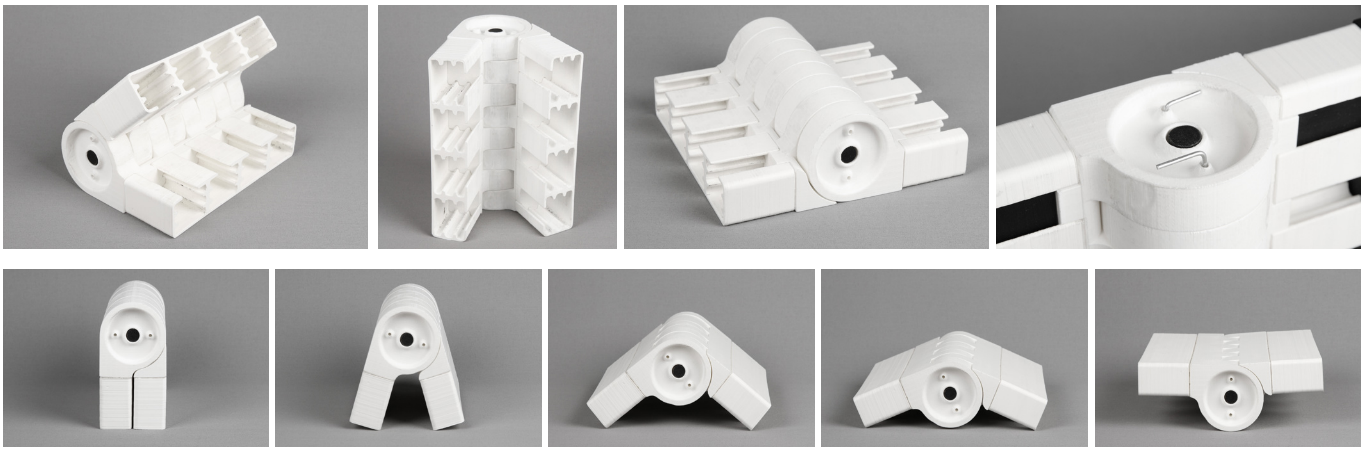

Figure 6.15 | Hinged Connection II made of PLA proceed with FDM printers, scale 1:2

[CONCLUSIONS]

7.1 Conclusions

The proposal design has developed an emergency bridge made of prefabricated, deployable trusses suitable for civilian but also assault and tactile mission applications.
The applied concept is an efficient and simple Warren Pony Truss in which its aluminum members fold to form a compact and easy to erect solution, based on the rules of Deployability, Modularity and Lightness and the requirements of speed, simplicity, flexibility and cost- efficiency.

In conclusion, the main distinguished features offered by DeMoLi system as an emergency bridge, with length that varies from 6-21m, a standard width of 3,00m and live load up to 40tons, are:

Deployable- Foldable Technology: *As an innovative method for civilian bridges based on hinged connections, which facilitates transportation and simultaneously provided a fast and simple erection.*

Modular Approach: *The bridge system utilizes modular construction extensively to satisfy a broad range of span requirements as the need arises. Modularity is also applied to make the transportation, maintenance, replacement and adaptability easier.*

Lightness: *DeMoLi is completely manufacture of aluminum alloys in optimized shapes, as a cost-efficient, lightweight and stiff material, which allow custom elements creating an ultra-light and cost-efficient solution. Readily available 6063 and 6082 alloys are used for many of the bridge components, while 43300 alloy is proposed for the casted hinges.*

Figure 7.1 | Visualization of DeMoLi12 in Pakistan

Technical Specifications:
Dimensions: *Length- from 6.00 to 21.00m, Width- 3.00m*
(similar to other applications)
Weight: *Ultra-light- approximately weight 400kg/m*
(lighter than alternatives[1])
Resistant: *Able to withstand heavy loads up to 40 tons.*
(similar to other applications).
Complete Structure: *The trusses and the railing are all-encompassing design.*
Storage Volume: *Volume in compact configuration is about 0.6m³/m and it can be transported on a simple truck*
(more compact than other alternatives).
Larger Element: *Dimensions of 3.00 x 1.50m and 270kg, able to handle by a crew of 6.*
Set-up Effort: *Erection time measurable in hours, not days or months*
(it is estimated less than existing solution resulting from the pre-assembled nature of DeMoLi)
Machinery: *System uses simple connections, without the need of special knowledge and tools for their assembly. Welding is used at all the permanent joints (within modules) in order to achieve the full strength of the complete structure More temporary connections like hinges and pins are applied for all the movable and on-site joints (between modules).The erection process requires just the transportation truck mounted crane, common tools and few volunteers.*

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[1] Compared with AIR-Bridge (According to Air-Bridge website [1.17]: “AIR-Bridge is the lightness system in the market”), which is 440kg/m is 10% lighter.

Figure 7.4 | Application of DeMoLi12 in maritime Roll-On Roll-Off (RORO) ramp

Figure 7.5 | Application of DeMoLi6 in a sensitive environment

Figure 7.6 | Application of DeMoLi in construction site

DeMoLi bridge system was designed for national military forces, national governments, NGO's and global mining corporations in mind for emergency purposes [Figure 7.1, 7.2 and 7.3]. However, it has a far broader applicability, providing unique temporary bridging solutions for civilian applications due to its adaptability, logistical benefits and fast deployment. Some of its potential uses are:

- DeMoLi system as a shipboard, maritime Roll-On Roll-Off (RORO) ramp for military and commercial transport vessels, facilitating equipment transfer in undeveloped or damaged ports [Figure 7.4].
- DeMoLi could provide access to areas without roads or across terrain with natural gaps in sensitive environmental areas, avoiding potentially fragile landscape [Figure 7.5].
- DeMoLi as a temporary bridge on construction sites, providing a simple, effective solution for construction companies, who need to provide temporary access solutions. By applying DeMoLi the access across trenches and excavations for pedestrian traffic but also construction vehicles is achievable [Figure 7.6].

Finally, the concept can be also available for rent or purchase.

7.2 Further Development

While the DeMoLi bridge system is already well developed, further steps are expected, related to the weight and the geometry of its structural components, but also to the length and loading capacity improvements. Moreover, in a further development phase, issues regarding the deck and its deployable capability or integration to the whole system must be also considered.

These further conclusions are analytically drawn as:

1. Lightweight

Based on aluminum material combined with an effective way of shape and production processes, the proposed truss bridge becomes an ultra-lightweight structure.

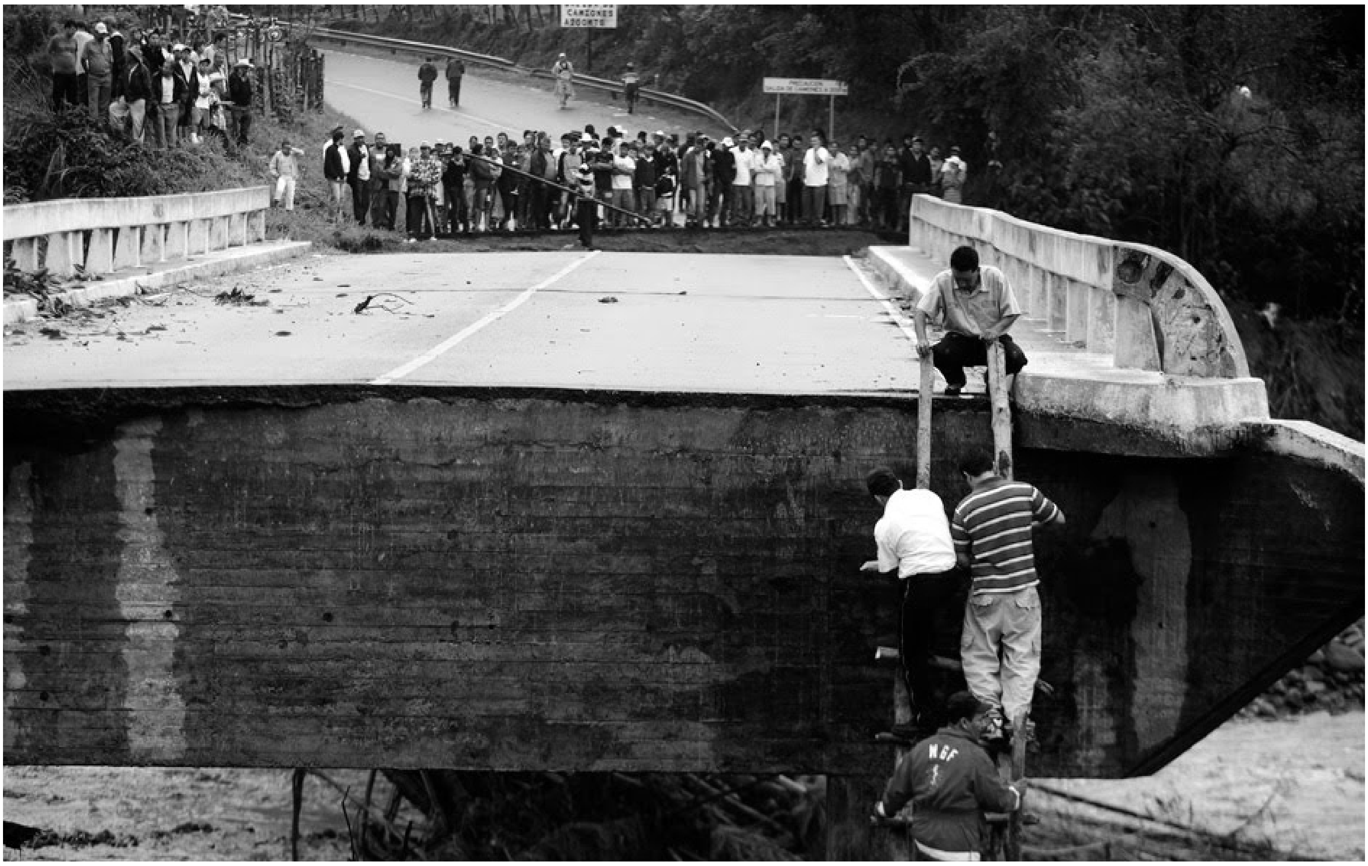

Figure 7.2a | Bridge collapsed following a 7.2-magnitude earthquake in Bohol Province, the Philippines on 18 October, 2013 [4]

Figure 7.2b | A Potential application of DeMoLi12 in in Bohol Province, the Philippines

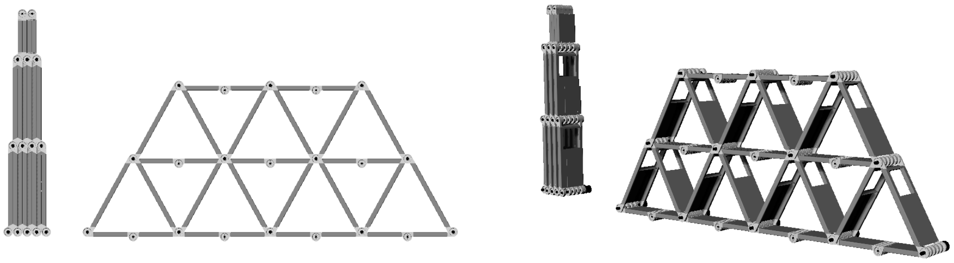

Figure 7.7 | Double height solution of DeMoLi6

Although aluminum is suggested as the most cost-efficient solution, there is also the option of CFRP-GFRP composite meterials as a more expensive but even more lightweight solution. The combination of these two composites materials can be developed to reduce the deformation of GFRP due to the low Young's modulus and simultaneously keep the price and the weight at lower levels. CFRP-GFRP composite elements are formed by reinforcing the GFRP members with unidirectional carbon fibers. [5.2]

2. Form Optimization

The FE analysis showed the feasibility of the proposed geometry solutions. The measured maximum vertical displacements are less than the admissible deflection and the maximum stresses do not exceed the ultimate limit state loading levels. Therefore, both the stiffness and strength are within the design requirements. In a further development step, design verification, laboratory tests and improvements through an extensive Finite Element Analysis and 1:1 prototypes will finalize and optimize the specific geometrical design of all the associated elements such as the general geometry of the truss, the shape of the hinged connections (following the rules of casting) and the cross sections of all the extruded element.

3. Length and Loading Capacity Improvement

Narrow down research aims early on to an achievable solution. Hence, avoiding of taking on something to an undesirable way several limitations were set from the beginning. Two of the major limitations of the DeMoLi Bridge design were its length, which is limited to 21m and its loading capacity, with the restriction of 40tons.

A challenge for a further development will be to find a sufficient way to exceed these limits, a step easy achievable due to the modular natura of the bridge. The basic idea of this will be to create hinged connections able to accommodate more elements by increasing either the height or the width of the structure or even both of them. As it is shown in Figure 7.8, the structure combines two trusses on the top of each other creating a double-height truss. In this way, the concept of DeMoLi can be extended by the addition of a pair of diagonal elements in hinged connection I, while the hinged connection II and all the horizontal elements remain the same. The resulting structure will be folded in the same way, while its double-height or even triple-height will make increase its span and its loading capacity. By this argument, it can be shown that any potential length and loading capacity will be possible and consequently its flexibility will be improved. Aspects related to the transportation (the height of the structure in compacted configuration) and erection have to be further considered.

Following this concept, the components can be put together in a number of configurations covering a range of spans and capacity requirements.

4. Deployable Deck

Another further development aspect is related to the decking system. Until now it is based on a modular concept, however as it was shown in erection time-line [Figure 6.8], this increases the erection time. If the truss can also follow the rules of deployability (pre-fabricated and pre-assembled elements that can be transformed from a close compacted configuration to a predetermined, expanded form, in which they are stable and can carry loads) the erection time can be decreased.

Figure 7.3a | Loma Prieta Earthquake damage on Bay Bridge, in Northern California on 17 October, 1989 [5]

Figure 7.3b | Application of DeMoLi12 in Bay Bridge, in Northern California

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Phase 6: Implementation

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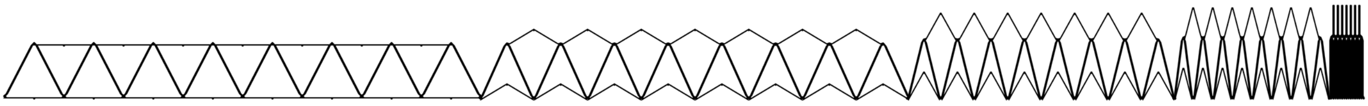

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Faculty of Architecture & Build Environment
MSc in Architecture, Urbanism and Building Sciences
Building Technology Track
Sustainable Design Graduation Studio
Master Graduation Thesis
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