P2- Research paper on plastic composites & earthquakes

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Research Paper

What are the suitability and applicability of plastic composites as an earthquake proof building material when looking at the structural and architectural features?

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Introduction to the plastic typology and classification as a building material

The word plastic derives from the Greek word ‘plastikos’. This means to form or to mold. This words points at the materials ground behaviour to assume new form or shape (Uffelen & Steybe, 2008, p. 5). Plastic consists of range of synthetic or semi-synthetic long molecule chains (polymers). Semi-synthetic polymers are modifications of natural polymers. Synthetic polymers, the more common type, are usually created from petrochemicals. These consist of an endless repeating basic unit, called a monomer.

Plastic materials are quite old. The early plastics were all bio-derived materials. The Mesoamericans for example had natural rubber, and they used it to make balls. The first man-made plastic has been invented in the 19th century. This plastic was developed by Thomas Hancock, a hard rubber. This half synthetic plastic was a vulcanised form of rubber. A few years later Schönbein developed the first thermoplastic resin (Aguado Alonso & Serrano, 1999, p. 2). This cellulosenitric, an acid also called ‘schietkatoen’ in Dutch, is a half synthetic polymer made from using sulphuric acid on cellulose fibers of wood or cotton. He is being considered as one of the first real producers of man-made plastic.

Until the Second World War this product used to be only produced in small quantities. Close to the Second World War there was a shortage in natural polymers like rubbers. In 1935 they invented polyether and in 1937 they developed polystyrene. The development of high density polyethers was an important step into the commercialisation of plastics. The used these polyethers for weapon parts. Where in 1934 only 10.000 tons of plastic were produced world-wide, that number reached 1.000.000 in 1949 (Uffelen & Steybe, 2008, p. 6). From then on plastics have an increased importance in the world. They are being used for piping, cars, planes, adhesives, foams, packaging etc. They play an increasing big role in architecture as well, due to their good strength-weight ratio and due to its different aesthetical properties compared to traditional building materials.

Due to the different manufacturing processes plastics show a wide range of property variations. The hardness and elasticity, and the thermal remoulding are some of the main properties. There are four main types to classify most of the types: thermoplastics, thermosetting plastics, elastomers and polymer fibres (Mike Ashby, 2016). The last one is classified under composites. A composite is a solid material that is obtained from mixing two or more different constituent material elements. The result is a new substance with new properties, where the mixed elements have retained their individual characteristics. There are different types, but the interesting types in case of weight, strength and elasticity ratio are polymer matrix composites (PMC) (Sheikh-Ahmad, 2009, p. 74).

Different types of polymer construction material will be investigated in this report. First we look into what basically happens to a building during an earthquake, and what the most important properties are for a material during an earthquake. While this whole investigation has the goal of making a structural reinforcing expansion to save heritage, that is threatened by earthquakes, we’ll go deeper in how Groningen heritage is behaving during an earthquake. The fourth chapter there will be made a comparison of the strength, weight and ductility. After that chapter we will go further in the application of this material and connection methods. Following this chapter we’ll dive deeper into the architectural properties of the specified materials. All these steps are mentioned in a material selecting strategy proposed by Ashby (M. Ashby, Shercliff, & Cebon, pp. 29-43). Parallel to this strategy some calculations will be made using literature and the CES-software to prove the benefits of plastic composites in earthquake resilient architecture. This storyline is in the appendixes and provides deeper information. The conclusion should give an impetus for the next phase in the graduation design and research. The total report shall give an overview of what happens to a building in an earthquake and the benefits and possibilities of different plastic composites.
What happens to a building when an earthquake happens?

Every year there are earthquakes in the Netherlands. These earthquakes are in Groningen, one of the most northern provinces of the Netherlands. These earthquakes are an indirect result of the gas drillings of the NAM, the Dutch earth gas company. When the gas is being drilled, the natural gas containing layer losses pressure. This gas crust layer is being pressed and along the cleavages the pressure differences are increasing. Eventually the earth crust layers sag. These sudden shifts cause earthquakes (NAM, 2015, p. 8).

These seismic forces are inertia forces and cause a lot of damage to the buildings in Groningen. When a building experiences acceleration, through a shaking ground, an inertia force is generated. This force can be quantified with Newton’s Second Law of Motion: $F = m \times a$. $F$ is the inertia force. $m$ is the mass of an object. This is determined by dividing its weight by the acceleration due to gravity. $a$ ($m/s^2$) is the acceleration. This is the primary equation for seismic resistant design (Charleson, 2008, p. 16).

![Image 1 & 2: Earthquake acceleration on a building structure.](image)

Inertia forces act within a building. They are internal forces. Horizontal accelerations transfer up through the superstructure of the building as the ground under a building shakes sideways. The inertia forces flow throughout it. Inertia forces act on every item and every component. Every square metre of construction, like a floor slab or wall, possesses weight and therefore mass (Charleson, 2008, p. 16).

![Image 3: Force flow through the structure.](image)  ![Image 4: Centre of mass point.](image)

But we can take the analogy even further between gravity and the inertia forces. The sum of gravity forces acting on an element can be assumed to act at its centre of mass (CoM). Since the most of the weight is concentrated in the roof and floors we can simply say that that point lies in the centre of a plan.
The CoM lies at the middle point of every floor and is influenced by horizontal forces as well, like wind. Wind pressure, or wind loading, acts upon external faced surfaces. This is important during an earthquake: when an earthquake reaches a peak in acceleration, the wind could have a strong gust at the same moment. These last forces are only important when structures consist of long-spanning floor or roof structures.

![Image 5: CoM and the bending moment.](image)

For example, when the earth shakes and the building moves, the hinged structure and the higher floors have an inertia movement which can be depicted like an egg on a table. The egg, when placed perfectly on the bottom, will stand still. When the table (the earth crust) is being moved horizontally, the egg (the building structure) rolls over, creating a moment at the connection between the structure and the earth’s crust.

![Image 6: Egg on the table](image)

![Image 7: Egg on a moving table.](image)

In most cases in Groningen these problems are being solved with external structures which supress the bending moments and prevent a part of the damage. Enough strength is needed to hold this building. You need sufficient structural strength to hold the shear forces caused by the seismic forces (Charleson, 2008, p. 25). These Groninger buildings, supported this way, are rendered unliveable, because of the ungainly structures running through and around the building.

![Image 8: Reinforced egg on table.](image)

![Image 9: Reinforced egg with forces.](image)
What damages do earthquakes cause in Groningen?

The building tradition in Groningen basically consists of structures of wooden skeletons with brick walls and tiled roofs (van Olst, p. 64). These buildings have proved to undergo a lot of damage as a result of earthquakes (NAM, 2015, p. 13).

The moment forces create a lot of damage to brittle structures. Cracks appear and due to a bad ductility of the brickwork, this means a momentary overload, which results in crushed or subsided toes, or diagonal cracks in the corner points of the brickwork.

A lot of damage appears on the brittle structures due to these combination of forces: bed-joint sliding, rocking, diagonal tension and toe crushing. The governing behaviour of the masonry wall or pier is the one with the lowest capacity.

The bond between walls, floors and ceilings are simple diaphragms. They resist the inertia forces from their own mass and those of elements like beams and walls attached to them. Transfer diaphragms, the ones to the right, resist the same forces but then the horizontal forces from one vertical bracing system above to another below. Transfer diaphragms are usually far more heavily stressed than simple diaphragms and consequently need to be considerably stronger and may not be able to accommodate large penetrations. The high stresses that come need extra support or reinforcement or else cracks will appear at the stress points. These connection points need to be strong and ductile as well (Charleson, 2008, p. 51).

These high stress points are mostly the fatal points on the structures in Groningen. When a building is shaking during an earthquake, the moving forces are redirected in the structure (following Newton’s second law). In most cases the forces surpass the yield strength and the mass starts to sway. Every structural system has an own calculable frequency. But when the natural frequency of the structure is close to the frequency of the earthquake, they add up (Walraven & Vrouwenvelder, pp. 5-11). This is called a resonant rise. Therefore we must not only take the acceleration speed of the earthquake in account, but the matching vibration period as well. This ratio can be defined as $\alpha_{dyn} = S_e / a_g$, with $a_g$ as the highest acceleration of the earthquake and $S_e$ as the response acceleration. $\alpha_{dyn}$ can be seen as the acceleration in the vertical axe. Following this statement the maximum horizontal force will be $F_{el,max} = m \cdot a_g \cdot \alpha_{dyn}$. As a rule of thumb the natural period of vibration is 0.1 second per storey (Charleson, 2008, p. 20). Most buildings in Groningen have 1 or 2 storeys. This means that a short building, with a small natural period of vibration, will be shaking heavily at a small maximum shaking acceleration of 0.2g (see appendix 3), the kind of earthquakes that happen in Groningen.
But the forces of an earthquake can be reduced by ductility. This is a grade of plastic deformability. With ductility a building can resist collapsing during an earthquake (Chakrabarti, 2007, pp. 25-30). A good example is a tree and a blade of grass. When wind is blowing the blade of grass is deforming, but the tree stands still. But when the wind is that hard and the acceleration reaches certain values the tree snaps, but the blade of grass only deforms. So, when the elastic limit is reached the structure can snap or it keeps strength by deforming. Glass for example suddenly snaps when it reaches its elastic limit. Through elongation it can reach more strength. Ductility is also used by earthquake experts to describe the materials ability to absorb kinetic force. After a certain elongation the material can absorb some of the inertia force caused by the earthquake (Chakrabarti, 2007, pp. 25-30).

This reduced force be defined as \( F_{\text{max}} = (1/q) \cdot F_{\text{el,max}} \).

\( q \) is the behaviour factor. \( q = \sqrt{2\mu - 1} \), where \( \mu \) is the displacement ductility. Image 12: knacked tree.

\( \mu = \mu_{\text{max}} \) (maximum elongation limit) / \( u_y \) (yield strength) and can play a big role in the calculation. The final general calculation will be \( F_{\text{max}} = m \cdot a_g \cdot \alpha_{\text{dyn}} / q \) (Walraven & Vrouwenvelder, pp. 5-11). Cracks appear through the low ductility of the stress points of the buildings in Groningen. After an earthquake these are visible at the beam and wall connections, and the arches and joists above windows and doors.

Image 13 & 14: damage earthquake in Groningen (http://www.gevekebouwenontwikkeling.nl/).

Buildings and/or building parts in Groningen can be divided into (sub-)types. The towers and the more massive buildings. The towers or chimneys are heavily affected by earthquakes (Asteris & Plevris, 2015), while the bending moment is increased. This means, that when a building shakes the tower leans over and big deformations occur (Cakir F., Uckan E., Shen J., Seker S., & B., 2015). A big problem with more massive building parts is the asymmetry in the floor plan. Through irregular shapes in a building plan torsion is created, which can create more bending moments in the plan.

In broad terms there are three building strategies (Walraven & Vrouwenvelder, p. 7). The first option is building a very stiff and strong building. This is quite an expensive solution, because every connection should be strong enough to withstand an earthquake. Furthermore, it is very hard to predict the force of an earthquake. The second option is to build a weak, but very ductile structure. Plastic deformations will occur everywhere during an earthquake. Damages to extra parts, like brick facades, will occur, but the building will not collapse. The third option is a more elasto-plastic solution. Only deformations in moderation will be allowed. Certain plastic areas can take on the plastic force. This solution works at moderate seismic areas, where limited damage should be fine. This last option should fit the well in the earthquake story of Groningen. However, it is probably a problem with the brick buildings to pass on the kinetic force, while the bricks have such a low natural period of vibration. Even before the forces are passed, the bricks will start to crack. Asymmetry problems in the floor plan can be solved in an architectural way. By making the floor plan more symmetrical, torsion in the horizontal plan is being reduced (Charleson, 2008, pp. 27-31).
Why a plastic composite considering the ductility, density and strength?

Prior to the report I have set up the goals of my project. The project is about a smart reinforcing extension, that can support the building during an earthquake, doesn’t downgrade but upgrade the architecture of the heritage and can be removed after a 50 years. We should not forget that not an earthquake kills people, but an unsafe building structure does (Chakrabarti, 2007, p. 19). Nevertheless, an earthquake structure can be more than just a safe structure. According to these goals the expansion should meet the following requirements:

1. It should protect heritage.
2. It should keep the facade visible.
3. Be ahigh-grade, preventive solution.
4. Be a solution for the coming 50 years.
5. It should prevent gross damage by earthquakes to the building.
7. The expansion must be a sub-terrain visible solution.
8. Case show for making heritage earthquake proof.
9. Should limit the amount of damage caused by mounting to the original building.
10. The expansion can be demounted without leave coarse damage.
11. The expansion is not a continuation of the architectural style of the heritage. Through the use of a contemporary material and style the expansion will form an separate addition.
12. The expansion should fill up the asymmetric points, making the building more symmetric and should limit the horizontal torsion forces in an earthquake.
13. Use of strong and light contemporary materials.
15. The whole reinforcing package should be applicable on other buildings in other regions, for example the seismic area in Italy.

When choosing the preferable properties different aspects can be separated, therefore we use Ashby’s mentioned selection strategy (M. Ashby et al., pp. 29-43). When making a selection in the material there should be looked at the constraints the material should meet. The goals should give a starting point for defining these properties. This translation step is being followed by the screening of the material: the material is being eliminated that does not meet the constraints. The survivors are then taken to the next step, the ranking step. They are ordered by other criteria, like excellence, cost and aesthetic qualities. After that there is being looked how to design with them, and how they can be shaped. The shaping part is rendered important due to the possible connections and mount ability of the external structure. The shaping possibilities will be decisive in the selection. The chapter after that we will look at the architectural properties.

The first step is summed by the goals above. Following point 1, 2, 5, 6, 13 and 15 the building should not have too much mass. In Groningen a lot of the buildings are reinforced with ungainly reinforcements that keep the building at its place through tensile forces. Through the mass of these expansions, the building are being rendered unliveable. The basis of my approach will be the same, but then, following my goals, it should not add at a lot of extra mass. My goal is to limit the rate of visible coverage of the building exterior. Plastics are mostly rendered for having a favourable strength-weight-density ratio. If we look at Newton’s Second Law of Motion: \( F = M \times a \), we see that the total mass is of big influence (Charleson, 2008, p. 18). Following this equation we should limit the mass. We want a material that has relative much tensile strength in combination with a low density. The higher the density, the bigger the total amount of mass, the bigger the total inertia force.

If we compare the density and tensile strength we can see which material groups are the most favourite. When looking at appendix 1, we can see that a polymer carbon composite is more
favourable. But can it be proved as well? What is the difference in used material compared to for example a quite strong and ductile material like steel or iron? An example is taken out of the office reinforcement by Kengu Kuma, who has used carbon fibre reinforced polymers to keep the building together in an earthquake (Seiren, 2015). Following appendix 2 & 3 we can see that the compared materials, steel, iron and CFRP show that CFRP’s are the lightest solution with the most tensile strength. This is after all a very basic approach. We don’t look at the angle of the rods, the compressive strength or the ductility. Ductility is an important factor in seismic design. Because the natural period of vibration causes a lot of damage to brittle structures, like brickwork, when it gets higher ($T = 2 \pi \sqrt{M/K}$) (Charleson, 2008, p. 23). The Young’s Modulus says a lot about the brittleness. The higher the more brittle, the lower the more ductile (M. Ashby et al., p. 39). The CFRP still for example has quite a high Young’s Modulus. We know from the last chapter that ductility is quite important.

The magnitude of the earthquake acceleration is heavily influenced by the ductility and by the natural period of vibration. Ductility can be thought of as the opposite of brittleness (M. Ashby et al., p. 4). A ductile material has a larger elastic range. A ductile material deform plastically and snaps when it reaches its final elongation, as we saw in the tree example in the last chapter. The material deforms but remains its bending strength. When an earthquake acceleration exceeds the strength of a brittle material, it snaps. Therefore a ductile structure in earthquakes is desirable, because it will bend first (Charleson, 2008, p. 25). Through the plastic deformation a lot of the kinetic force can be absorbed. This could be realised in the shape of dampers. That is why plastic composite polymers could be a good idea in earthquakes. This can be shown as an egg on the table which is being hold from both sides with a spring. Dampers increase the natural vibration time. These sides move as the table move and, through their ductility, absorb a part of the inertia force: the egg will not tumble.

Following goals 1, 5, 8 and 13 we need a light and ductile material. Following appendix 4 we can see that a good ductile material would be a material with a favourable yield strength ($\sigma_y$), or elastic limit ($\sigma_{el}$), and elongation (M. Ashby et al., pp. 112-114). Young’s modulus is a way to look at the stiffness, but does not say something about the elastic limit. Following appendix 4 a Polyamideimide proves to be the best material. But, after the calculation in appendix 6, we can see that some materials have such a high yield strength, that ductility is not needed, like kevlar carbon fibre and spectra polyethylene. However a lot is dependent of the shaping; the material should be applicable when making structural and architectural elements (Rahim, 2002, pp. 72-83).

However, while the bricks have a very short natural period of vibration it will be hard to transfer the kinetic force into the expansion; the bricks will probably crack before the forces are redirected (Cakir F. et al., 2015). According to goal 5 this is something we want to prevent. Therefore there are two solutions. The first solution is prestressing the building: through tensile forces we make the building more like a box. This means the building works as unit. The second solution is by making the original brick wall more ductile. When the brick wall is more ductile, it can easily direct the forces to the expansion. In both cases the inner and outer connections between old and new are very important.

Image 15: Ductility (physics.stackexchange.com).

Image 16: egg with absorbed forces.

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How can a plastic composite be turned into an appropriate building material?

In the third step of the strategy we are looking at other properties, than tensile strength and ductility (M. Ashby et al., pp. 29-43). It is very important to look at the possibilities of shaping the material. After all we do need the plastic polymer to be turned into constructible parts. When the carbon fibre proves to be the right material, we have to look at the applicability. Polymers are normally easy to mould in complex forms (M. Ashby et al., p. 470). It is however a different story when talking about polymers with fibres. Carbon fibres are normally woven into the material to give the material more strength. The strength lies in the direction of the fibre.

On a microscopic level, polymer composites are a heterogeneous material systems. The directionality of fibre reinforcement can be tailored to support the direction to absorb anticipated directional load. While the materials do not predate a given application, their exact composition and form can be determined to meet with desired performance criteria. In this case that would be the connection between the structural parts (beam, column etc.), and the (f.e. curved) shape. For example, form and structure are no longer categorically distinctly, but they may flow in and out of one another, in order to optimise the synergy of the force flows (Rahim, 2002, p. 76). The polymer composite surface is a product of the synthesis. These materials are generally called FRPs, fibre-reinforced polymers.

The machinability of materials refers to the grade of difficulty of how the can be shaped (Sheikh-Ahmad, 2009, p. 151). It is not easy to get a consistent and quantitative measure of properties and machinability in FRP. The problem is getting fibres in the correct shape. The properties are determined by the fibre volume fraction, the matrix and the fibre orientation. In the case of the earthquake structures it is desirable to have costum parts. While every example of heritage proves to be unique, the connections between the building and the expansion will be the most complex part to design. The force flow will be of big importance. One way to control this flow is by fiber orientation through turning.

The fiber orientation angle has a major influence. When turning the cutting in a plane is perpendicular to the axis of rotation. The fibres are laid in parallel planes and parallel in the rotation axis. The end of the ply is the chord of all fibres. The helix angle should almost always be 90 degrees (Sheikh-Ahmad, 2009, p. 154).

Milling or trimming of FRP’s is one of the most common ways of manufacturing structural parts. (Sheikh-Ahmad, 2009, pp. 168-170). Compared to metals they do it in a much smaller scale. This is because of the net shape of the fibres. When this net is broken, it loses a lot of the wanted properties. They mostly just keep it at deburring and trimming. When milling more cutting edges are engaged and therefore a lot more complexity is added. There are two main ways of milling: up-milling and down-milling. In both ways the quality of the fibre direction is influenced and the cutting edge is depended on the quality of the machined surface. However this last method is only suitable for cables and ply. In the increasing demand of complex FRP parts the difficulty of secondary machining is increasing. Non-traditional way of machining are more preferable for making stronger FRPs in complexer shapes (Sheikh-Ahmad, 2009, p. 244). Waterjet Machining, laser machining, ultrasonic machining and electrical discharge machining are example methods. Abrasive waterjet machining (AWJ) is by far one of the most widely implemented non-traditional method. This method has as advantages the high production rates, great flexibility and the capability to produce complex contours and shapes (Sheikh-Ahmad, 2009, p. 285). This method is probably useful in the upcoming design process. The disadvantage of this method is delamination and the waviness in the cut kerf.
The fourth and last step of the strategy of Ashby is about research the family history of top-ranked candidates (M. Ashby et al., pp. 29-43). Carbon fibres are quite new in architecture, but there are already a few examples of polymer carbon fibre buildings. More examples of FRP and CFRP buildings and structures are appearing and prove to (until now) to succeed. (Uffelen & Steybe, 2008)

The first example is this Polish Bridge, a collaboration between Mostostal Warszawa & Warsaw University of Technology (Shury, 2016b). This small bridge is the first example in the world of a bridge being made out of FRP beams. The girders are first made by laying out the mattresses of carbon fabrics. These are laminated until a thickness of 35 millimetre is being reached. The dry fibres are being impregnated with resin using a vacuum pump. This process of fusion results in composites with a high quality (Siwowski, Kaleta, & Rajchel, 2015). The FRP matrix disperses the force flow. One of the biggest problems proved to be the unknown factors. There are currently no approved standards and legal guidelines for constructing with these kind of girders. Most factors are tested in the laboratory by acoustic emissions and right after constructing on the real life bridge. They placed 4 full trucks on the bridge to test the real bridge. The bridge proved to be really strong enough. A advantage of this method is the possibility to cut elements on site with a grinder. Image 18: The FRP bridge in Błażowa.

The second example is the Apple theatre roof at its new headquarters in Cupertino, USA (Shury, 2016a). It is a cylinder-shaped with 44 radial panels that span 21 meter. Its weight is only 80 tons in total. The whole roof is freestanding, leaning on the glass only. Structural specifics are still undisclosed, but it proofs the strength versus density possibilities. Image 19: The assembly of the roof in Cupertino.

The third example is about the gigantic FRP construction robots in Stuttgart, Germany (Mairs, 2016). These robots weave tailor-made structures. The resin-coated structures are put in a big oven and cured. After that they are detached from their framework. The possibilities can reach for more complex and useful structures than just by moulding. The same thing is possible with mini robots (Shury, 2016c). They can weave a custom structure in place without the use of the big oven. More complex structures are possible with this. They could even be a possibility for the structures in Groningen.

Image 20: The gigantic FRP construction robots.

As said in the last chapter brick doesn’t have the plasticity and flexibility to pass on the forces to the addition. The bricks will likely crack before they can pass on the forces. (Chakrabarti, 2007). In any case, if we want to guide the force flow to the expansion, the connections should be designed very carefully. AWJ or the vacuum pulling method can be a good solution. AWJ is a more wide spread, but offers some difficulties in delamination and at the cutting kerf. Following appendix 5 polyamideimide (PAI) with glass or carbon fibre, a polyetheretherketone (PEEK) are the best choices. Due to the durability and their sensitivity the other material choices are less favourable. The typical uses scheme (table 11 in the appendix) does not tell anything specific about the possibilities to shape it. Therefore, when looking at the production possibilities and the appendix 5, a PAI or PEEK is the most favourable material. The material surfaces can of course be treated, so the other materials should not be neglected as well.
What are the architectural properties of the plastic composite as a building material?

The third step is about screening all the materials that can do the job (M. Ashby et al., pp. 29-43). We have had the fourth step in the last chapter. However we have not looked at the other secondary properties, like not at the architectural properties. In a way shaping possibilities is part of the architectural properties, but texture and colour have not been mentioned yet. These specifics will be looked at in this chapter.

When we look at the texture of the material we can find some similarities and differences between the materials. Following appendix 6, and earlier appendixes, we can see that the selected materials succeed at most demands. Some materials prove to be more flammable or affectable by light or water, but on the other hand they prove more ductile, better shape able or just cheaper. It is always in the balance.

Texture is one of the hardest and important architectural properties of the materials (Rahim, 2002, p. 75). There are different kinds of fibre, for example carbon, glass, aramide and polyethylene. These are also fibre types that are mentioned in the appendixes as part of the selected materials. Glass fibre is the cheapest and therefore the most standard. The fibres are quite visible when looking or touching the material. Which fibre and the way it is woven, pattern of interlacing, or knitted, the array of knots, can greatly affect the way the appearance of the material. FRP’s have mostly a smooth look with a visible fibre pattern.

The image on this page shows how different polymer composites look after tests. Different combinations of ravings and weave patterns are visible. The middle and left under sample show chopped glass fibre ravings. Some colour additives are visible as well. This image shows the variety possible between different textures, colours and how they are shaped.

![Image 21: from (Rahim, 2002, p. 75).](image-url)
But how do the specific materials named in the appendixes look. Texture and colour are of importance, but the ordering size and specifics as well. Here is an overview of the five selected materials to complete the fourth step of Asbhy’s strategy (M. Ashby et al., pp. 29-43).

PAI is available in mostly brown and tawny and has a smooth surface (Indiamart, 2016). The fibre pattern is visible on flat surfaces, but less clear on tubes on rods. The glass fibre enhances the strength. The material is opaque.

Image 22: PAI glass fibre.

PEEK has most of the same properties as PAI, but is more smooth. Mostly has a lighter colour and a reflecting appearance, but in combination with carbon fibre it is light or dark grey. This has as the other FRP’s (PAI and PA66) a comparable texture and colour.

Image 23: PEEK carbon fibre.

PA66 is a bit the same case as the other materials, but is more common. It is definitely the cheapest version and can easily be ordered online. It is comparable with the FRP used in Poland on the FRP-bridge. This bridge has been constructed with a combination of different types of glass fibre on top and carbon fibre on the bottom flannels. The epoxy resin makes a bit different look. (Siwowski et al., 2015).

Image 24: CFRP.

Kevlar aramide carbon fibre has a bigger stiffness and tensile strength that glass, but less than carbon fibre (Polyestershoppen, 2016). The fibres don’t take resin by itself and it will delaminate quite easy. The advantage is that it is better against a point load. The downside is that it can be used only once under high stress, like with crash helmets. This could mean for structural purposes that after a heavy earthquake the structural elements must be replaced. It can be combined with the carbon fibre, to get the benefits of both materials. The fabric has a rough surface with very visible fibres. Kevlar aramide is yellowish and carbon fibre, as visible in above mentioned examples, is dark grey. In combination with ceramics or polymers it can be used in architecture. An example is Villa Nurbs on the Costa Brava (Geli, 2010). The substructure is made of kevlar carbon fabrics.

Image 25: Kevlar aramide + carbon fibre

Image 26: Kevlar in architecture.

Image 27: Spectra texture.

Spectra 900 polyethylene can only be ordered in very thin lines. The transparent lines, normally used in fishing lines and ballistic helmets, can be woven into a pattern (Honeywell, 2016). There is however no example known of this material in architecture.

The FRP’s and Kevlar carbon fibre show a possibility to be used in architecture. The examples, like Villa Nurbs and the bridge in Poland show that it is possible to use these materials in architecture. While most of the materials are only used in specific parts for aeroplanes or special equipment, it is a matter of further research and testing on how to turn these materials in the desired architecture.
Conclusion

After the four steps of strategy, we have got a selection of materials that can be used in the (M. Ashby et al., pp. 29-43). As mentioned in earlier chapters the steps are: (1) translation of the design requirements, (2) elimination of the materials that cannot do the job, (3) the ranking of which material does his job best and (4) the documentation and background of every material. As a result of case shows, comparisons and calculations only a few materials were left and mentioned as the selection. These materials are PAI, PEEK, PA66, kevlar aramide carbon fibre and spectra polyethylene fibre. As named in the design goals on page 8 we wanted a sub-terrain light weight expansion for the heritage in order to protect the heritage. The expansion should be in a contemporary style, keeping the original heritage façade as visible as possible, be functional usable and be demountable, when the gas drillings are over. After, step 2, testing the material database of CES (Mike Ashby, 2016) we found that plastics and composites would be a good candidate, eliminating many other materials. After that we looked at other properties – step 3 -, like architectural properties and shaping possibilities. The case shows – step 4 – left us with this selection of materials.

The special thing with plastics is that it is not just a material with certain properties, but it has a capacity to transform as well (Bell & Buckley, 2014, p. 7). In the big architectural discourse plastic remains largely invisible. First or later generation materials like stone, wood, brick, concrete & steel are being viewed as more natural, aesthetic and socially acceptable materials. However, as my investigation points out, the plastic (composites) have far more stretched possibilities. I think it is only a matter of time before plastics are embedded in our new found building traditions. In any case do the plastic composites form the best solution when protecting heritage in Groningen following my design goals. While shaping and processing possibilities are still in its infancy the case studies show already some promising results. For example the FRP bridge in Błażowa (Siwowski et al., 2015) shows a quite efficient assembly by normal construction workers. However they are leaded by empiric project leaders from Mostostal and the Warsaw University of Technology, the onsite possibility to cut and grind the material shows the first steps of the plastic embedding in our construction culture.

Shaping and processing possibilities are decisive in the last steps of the selection strategy. PA66 is one of the most common composites and therefore one of the most customary and cheapest options to be used in the expansion. However, like the FRP-bridge in Poland, there is always an option to combine different fibres or composites (Shury, 2016b). There they used different mattresses of carbon and glass fibres on the plastic. PEEK & PAI should not be ruled out, while they have corresponding applications. PEEK is very expensive, but PAI is not that far from PA66 in price. PAI even has better ductile abilities. Kevlar-carbon and the other side has a different approach. As a very strong material it doesn’t need ductility that much, but the costs are higher than that of PA66. But, like in Villa Nurbs, the architecture of it is proven (Geli, 2010). Spectra polyethylene, as last of the materials, is probably not a good solution. It is the only transparent material, but the documentation shows that the typical uses and application are toom remote from architecture. Added to that, this material is almost the most expensive. At the end the favourites are PAI, PA66 and Kevlar-Carbon.

Further research, test-modelling, real-life modelling and designing should prove which material is the best application. As mentioned I have to find out if I can make the brick wall more ductile, or if I can pre-stress the building in a way that the ductility and strength of the expansion can do their work and prevent most of the earthquake damage on the heritage. This report should give an impetus for the design and modelling process: a good start for the investigation on how a structural part can be made out a polymer composite.. The most important aspects for the next phase are: (1) how can we get most of the inertia forces move through the connection to the more ductile plastic expansion, (2) how can the connection be made with as little damage to the heritage as possible and (3) how can the expansion be designed in a proper, architectural and aesthetic way.
Literature


van Olst, E. L. Building traditions in the Netherlands.

Appendix

Appendix 1: Plastics
The tables here show the comparison of density of tensile strength of most the materials. Due to the amount of materials these tables (Mike Ashby, 2016) don’t give a good idea of what kind of material is preferable. Following the strategy (M. Ashby et al., p. 36) named in the fourth chapter we need to follow certain steps which indicate the ranking of a material. One of the most important properties is the strength and the density. We probably need quite a lot of tensile strength, but the density plays a role as well. What if we put these properties in graph to each other.

Table 1: Density of materials.

As visible most of honeycombs, foams and natural materials are too weak. Most of the fibers and particulates, composites, metals and alloys, plastics, glasses and technical ceramics are strong enough. When looking at the weight we can see that most of metals and alloys, composites, part of the fibers and particulates and part of the technical ceramics are too heavy. But this scheme is still a bit to imprecise, therefore some pre-set limits could help.

Table 2: Tensile strength of materials.

Table 3: Comparison of all material groups looking at density and tensile strength.
When looking at the table there is still no much clear. We have to set borders for the materials. According to Newton’s Second Law of Motion: $F = M \times a$ we want to limit the mass and at the same time we want enough tensile strength (Charleson, 2008, p. 18). Let us say the maximum density is 2000 kg/m$^3$ and the minimum tensile strength is at least 200 MPa.

![Graph showing material comparison](image1)

**Table 4: Comparison of all material groups looking at density and tensile strength with limits.**

149 of the 3947 materials are left. The biggest survivors are the plastic composites, a few fiber and a few natural materials. Examples of high results in this case are carbon fibres. But it is not only tensile strength that matters, but compressive strength as well. An expansion like proposed should stand by itself.

![Graph showing material comparison](image2)

**Table 5: Comparison of all material groups looking at density and compressive strength.**

Here plastics (blue) show to be the best candidate. These are PA66 (long carbon fibers). They are however in another group, but they are comparable with the results of table 4. Therefore a polymer carbon composite (Mike Ashby, 2016) seems to be the best candidate.
Appendix 2: Mass of a typical Groninger house

For example a spacious countryside brick building in Groningen has 2 floors. The house is made out of bricks, has a wooden structure and a tiled roof.

Let’s say the building is 10 by 10 by 10 meters.

Brick has $3 \text{ kg/dm}^3$
Source: handbook draagconstructie

The floor between first and second floor has $1\text{dm} \times 100\text{dm} \times 100\text{dm} \times 3\text{kg/dm}^3 = 30.000 \text{ kg} = 30 \text{ tons}$. 

Image 28: typical house in Groningen (own image).

Let’s say that the floor downstairs and the roof structure has the double weight. Total weight of floor is then $5 \times 30 \text{ tons} = 150 \text{ tons}$.

The four isolated walls have a thickness of 2 dm

$4 \times 2\text{dm} \times 100\text{dm} \times 100\text{dm} \times 3\text{kg/dm}^3 = 30.000 \text{ kg} = 240 \text{ tons}$

While we have not regarded a lot of the other objects in the building, like foundation and other wall elements, we can say that we add an extra 10% to the building. So following this rough sketch an brick building on the Groningen countryside has a mass of 429 tons.
Appendix 3: Basic calculation

The region of Uithuizen has had some serious earthquakes in 2012. Following this image of the KNMI we can say that a future earthquake could have a velocity of 0.2 g \((1g = 9.81 \text{ m/s}^2)\) \((g = \text{the acceleration due to Earth’s gravity, equivalent to g-force})\).

Newton’s Second Law of Motion, \(F = m \times a\) makes then
\[ F = 429.000 \text{ kg} \times 0.2 \times 9.81 \text{ m/s}^2 = 842 \text{ kN} \]

Kenju Kuma used tensile strength to compare which material should be based. He says that through tensile strength the egg is kept as it place, so that the structure stays undamaged for the biggest part \((\text{Seiren, 2015})\). Enough rods thick enough can keep the egg at his place. Therefore we have to compare the density and the tensile strength \((\text{M. Ashby et al., p. 50})\) of different materials. \(\text{Image 29: Earthquake area (NAM, 2015).}\)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/dm(^3))</th>
<th>Tensile strength per cross section area (kN/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>7,2-7,9</td>
<td>0,20</td>
</tr>
<tr>
<td>Steel</td>
<td>7,5-8,0</td>
<td>0,40-0,55</td>
</tr>
<tr>
<td>CFRP (used in Kuma’s design)</td>
<td>1,75</td>
<td>1,81</td>
</tr>
</tbody>
</table>

\(\text{Table 6: material properties (Seiren, 2015)}\)

If we calculate the cross sections for the three materials compared we can see the differences. And if we say the egg (building) is supported from four sides, and the earthquake is moving in one of these direction, than the building should pulled towards the direction the earth is accelerating to.

The total \(F\) should be balanced out from the tensile strength * cross section.

Let us say that the rods have a diameter of 5 mm. The cross-section surface of on rod should be
\[ r^2 \times \pi = \text{area} \]
\[ 2,5^2 \times \pi = 19.6 \text{ mm}^2 \]

\(\text{Image 30: Kuma’s building (Seiren, 2015).}\)

If we take \(F\) and divide it through the tensile strength we get the total cross section needed to keep the egg at place:
- CFRP: \(842 \text{ kN} / 1,81 \text{ kN/mm}^2 = 465 \text{ mm}^2 \rightarrow 465 \text{ mm}^2 / 19.6 \text{ mm}^2 = 24 \text{ rods}\)
- Steel: \(842 \text{ kN} / 0,5 \text{ kN/mm}^2 = 1684 \text{ mm}^2 \rightarrow 1684 \text{ mm}^2 / 19.6 \text{ mm}^2 = 86 \text{ rods}\)
- Iron: \(842 \text{ kN} / 0,2 \text{ kN/mm}^2 = 4210 \text{ mm}^2 \rightarrow 4210 \text{ mm}^2 / 19.6 \text{ mm}^2 = 215 \text{ rods}\)

This means CFRP need is almost 4 times less rods than steel and 9 times less rods than iron. And while the CFRP density is much lower, the extra added weight due to reinforcement will be limited. Building mass is show to be one of the most important different properties. Let us the rods under an angle have a length if 15 m (the building is 10 m high). If we add rods mass to the equation we see in example of the steel, \(8.0 \text{ g/cm}^3 \times 1684 \text{ mm}^2 \times 15000 \text{ mm} = 202 \text{ kg of steel}\). For CFRP this will be only \(1.75 \text{ g/cm}^3 \times 465 \text{ mm}^2 \times 15000 \text{ mm} = 12 \text{ kg of CFRP}\). This adds up in the second law of Newton. The CFRP will add less weight than the steel.
Appendix 4: Choosing type of plastic

These are the properties of the materials in appendix 3. As visible the Young’s modulus still relative high. However Young’s modulus says more about the resistance to stretching, than about the ductility. Therefore there should be looked at other properties and compared with other materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/mm³)</th>
<th>Tensile strength per cross section area(kN/mm²)</th>
<th>Young’s Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>7,2-7,9</td>
<td>0,20</td>
<td>90-170</td>
</tr>
<tr>
<td>Steel</td>
<td>7,5-8,0</td>
<td>0,40-0,55</td>
<td>190-210</td>
</tr>
<tr>
<td>CFRP (used in Kuma’s design)</td>
<td>1,75</td>
<td>1,81</td>
<td>185</td>
</tr>
</tbody>
</table>

*Table 7: simplified properties used in Kenju’s project (Seiren, 2015).*

As mentioned in chapter 4 there are a few properties which can define ductility: yield strength (σy), or elastic limit (σel), and elongation (M. Ashby et al., pp. 112-114). Yield strength is the point where a material starts to deform and therefore important for the overall strength. If we put that, following the limits of appendix 1, out against the density, we can find out which materials can be suitable.

*Table 8: Yield strength versus density.*

But that is not everything. Yield strength points out the point when the material starts to bent. We want to how much strain the can tolerate. Normally it is measured in elongation (εf). This value is a percentage that points out the deformation before snapping (M. Ashby et al., p. 114).

*Table 9: Elongation versus yield strength.*

The materials that are probably the best are a type of polyamideimide (PAI) with some part carbon fiber. This is a polymer composite. Composites with fibres are mostly a bit weaker in compression tan they are in tension. That is because the fibres buckle on a small scale (M. Ashby et al., p. 114). However elongation is not a material property, because elongation is depended on the material dimension. More ranking will give an answer, like looking at the shaping or processing. These ways of processing are limited for every material and the material should therefore be applicable (Uffelen & Steybe, 2008, p. 3). Magnesium for example is not applicable in big construction parts when looking at the information provided in CES.
Appendix 5: Typical uses and other properties

As seen in the last appendix the best materials have certain properties. If we sharpen up the density, tensile strength and ductility properties we get some clear overview. Most of the steel materials don’t survive. That would be a type of polyamideimide (PAI) with glass or carbon fibre, a polyetheretherketone (PEEK), a polyamide nylon with carbon fibre (PA66), a kevlar aramide carbon fibre or a spectra polyethylene fibre.

According to the conclusions taken in the last appendixes we can say that these materials have the right properties. However, Following the strategy (M. Ashby et al., p. 36) we will go further in the application and shaping of these materials. The second step is about finding the material that can do the job. This third step is about which material is the best do the job. According to the CES-database these materials have certain appropriate applications. Furthermore, there are other properties of importance, than the mechanical and physical properties where we looked at in the previous appendixes. Durability and the processing properties. But first the typical uses. In the CES-database (Mike Ashby, 2016) these are the typical uses of these materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAI</td>
<td>Valves, bearings, electrical connectors, gears, parts for jet and internal</td>
</tr>
<tr>
<td></td>
<td>combustion engines, printed circuit boards</td>
</tr>
<tr>
<td>PEEK</td>
<td>Wire covering, injection moulded engineering products, film for flexible</td>
</tr>
<tr>
<td></td>
<td>pcb, resin in fiber prepregs, aerospace applications, radiation environments,</td>
</tr>
<tr>
<td></td>
<td>piping</td>
</tr>
<tr>
<td>PA66</td>
<td>Gears, cams, rollers, bearings, nuts and bolts, power tool housing, electrical</td>
</tr>
<tr>
<td></td>
<td>connectors, combs, coil formers, fuel tanks for cars, kitchen utensils</td>
</tr>
<tr>
<td>Kevlar aramide carbon</td>
<td>Tensile members, such as ropes and webbings</td>
</tr>
<tr>
<td>fibre</td>
<td></td>
</tr>
<tr>
<td>Spectra polyethylene</td>
<td>Ballistic vests, helmets and armored vehicles, sailcloth, fishing lines,</td>
</tr>
<tr>
<td></td>
<td>marine cordage and lifting slings, cut resistant glove and safety apparel</td>
</tr>
</tbody>
</table>

Table 11: Typical uses of the materials.

As shown above most of the materials are mostly used in smaller, special and more expensive applications that demand a light and strong material. But what about the durability:

<table>
<thead>
<tr>
<th>Durability</th>
<th>PAI</th>
<th>PEEK</th>
<th>PA66</th>
<th>Kevlar-carbon</th>
<th>Spectra polyethylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (fresh)</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Acceptable</td>
<td>Excellent</td>
</tr>
<tr>
<td>Water (salt)</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Acceptable</td>
<td>Excellent</td>
</tr>
<tr>
<td>Weak acids</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Unacceptable</td>
<td>Limited use</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Strong acids</td>
<td>Limited use</td>
<td>Limited use</td>
<td>Unacceptable</td>
<td>Limited use</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Weak alkalis</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Strong alkalis</td>
<td>Limited use</td>
<td>Excellent</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Organic solvents</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Limited use</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>Oxidation at 500°C</td>
<td>Unacceptable</td>
<td>Unacceptable</td>
<td>Unacceptable</td>
<td>Unacceptable</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>UV radiation(sun)</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Flammability</td>
<td>Self-extinguishing</td>
<td>Self-extinguishing</td>
<td>Slow-burning</td>
<td>Highly flammable</td>
<td>Highly flammable</td>
</tr>
</tbody>
</table>

Table 12: Durability.

Following these both tables we can see the applicability. Following table 12 kevlar aramide carbon fibre is not the best choice, due to its mediocre attitude against water. While the expansion has to stand outside, the best choice would be PAI, PEEK or PA66. The last two are not the best choice, because of their sensitivity for UV radiation or their flammability. Maybe the surfaces of these materials can be treated.
Appendix 6: Final calculation, transparency and costs

In the last appendix a preference has been made between the material FRP’s: PAI, PEEK, PA66, and fibre particulates: the kevlar aramide carbon fibre or spectra polyethylene. Looking at the durability (table 12) PAI and PEEK have the best results. But before going deeper into looking at the material appearance a final estimation of the ductility will be made. The earlier calculations in appendix 2 & 3 show a preference between material types when looking at density and tensile strength. However a very important factor, as has been shown on page 7, is ductility (Walraven & Vrouwenvelder, pp. 5-11). Assumptions and comparisons have been made using the CES-software. The importance however has not been calculated yet, and therefore has to be proved.

This formula rolls out of the comparison:

\[ F_{\text{max}} = m \cdot a_g \cdot \alpha_{\text{dyn}} / q \]

- \( m \) = the mass of the object.
- \( a_g \) = the highest acceleration of the earthquake.
- \( \alpha_{\text{dyn}} = S_e / a_g \), and \( S_e \) as the response acceleration.
- \( q = \sqrt{2\mu - 1} \), where \( \mu \) is the displacement ductility.
- \( \mu = \mu_{\text{max}} / u_y \) (yield strength).

We take the mass and acceleration used in the calculation in appendix 2 & 3.

\[ m = 429.000 \, \text{kg} \times 9,81 \, \text{m/s}^2 = 4208,5 \, \text{kN} \]

\[ a_g = 0,2 \, \text{s}^2 \]

For the factor \( \alpha_{\text{dyn}} = S_e / a_g \) we know by the rule of thumb on page 6, that the natural period of vibration on the vertical axe is 0,1 second per storey (Charleson, 2008, p. 20).

\[ \alpha_{\text{dyn}} = S_e / a_g = 0,2 \, \text{s} / 0,2 \, \text{s}^2 = 1 \]

The only needed value in the end that will differ in the selection of material is the value \( q \).

\[ q = \sqrt{2\mu - 1} \] is the formula when we assume equal deformation in the whole building. We can also assume an equal movement where \( u = u_{\text{max}} \), so \( q = \mu \). That last assumption only counts for slow big buildings with 7 floors or more.

One aspect, however, has been forgotten. The total equivalent of the horizontal force \( F \) on the structure has to be divided on the structure height (Walraven & Vrouwenvelder, p. 6). Normally a triangular distribution is assumed. This is shown in image XXX. To take the adverse effects of higher vibration modes in account structural designers normally add a fraction of the total force. This can be 10% in this case. The distribution of the forces on the different levels can be defined as:

\[ F_j = (F_{\text{tot}} - F) \cdot \left( (m_j \cdot h_j) / (\sum_{j=1}^{n} m_j \cdot h_j) \right) \]

where:
- \( j \) is the floor in the building we want to calculate.
- In the formula \( F_{\text{max}} = m \cdot a_g \cdot \alpha_{\text{dyn}} / q \) we want the force is at a maximum, thus we take the highest building level: the second floor. Therefore this formula can be skipped in this case. However, the relation formula about the force distribution can be used as a simplified method to design with earthquakes and is in line with the way how constructors think.

\[ F_j = (F_{\text{tot}} - F) \cdot \left( (m_j \cdot h_j) / (\sum_{j=1}^{n} m_j \cdot h_j) \right) \]

Image 31: the distribution of the horizontal forces between the different floors (Walraven & Vrouwenvelder, p. 7).
The value q, the ductility, is defined by the μ value. μ = μ\(\text{max}\) (maximum elongation limit) / \(u_y\) (yield strength). The five materials - PAI, PEEK, PA66, kevlar aramide and spectra polyethylene fibre – all have these defined values in CES (Mike Ashby, 2016). The \(\mu\text{max}\) can be found by looking up the values of the flexural strength in CES, which stands for the modulus of rupture.

\[
\mu = \frac{\mu\text{max}}{u_y} = \frac{\text{maximum elongation limit}}{\text{yield strength}}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>(\mu\text{max}) (maximum elongation limit in MPa)</th>
<th>(u_y) (average yield strength in MPa)</th>
<th>(\mu = \mu\text{max} / u_y) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAI (30% glass fibre)</td>
<td>350</td>
<td>98</td>
<td>3.57</td>
</tr>
<tr>
<td>PEEK (30% carbon fibre)</td>
<td>300</td>
<td>209</td>
<td>1.44</td>
</tr>
<tr>
<td>PA66 (30% carbon fibre)</td>
<td>226</td>
<td>195</td>
<td>1.16</td>
</tr>
<tr>
<td>Kevlar 29 carbon fibre</td>
<td>2,8 (\cdot) 10^3</td>
<td>2,8 (\cdot) 10^3</td>
<td>1</td>
</tr>
<tr>
<td>Spectra 900 polyethylene</td>
<td>2,3 (\cdot) 10^3</td>
<td>2,3 (\cdot) 10^3</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 13: Ductility.*

The resulted maximum force caused by the earthquake can then be calculated with \(q = v(2\mu - 1)\).

- **PAI:**
  \[F_{\text{max}} = m \cdot g \cdot \alpha_{\text{dyn}} / q = 4208,5 \text{ kN} \cdot 0,2 \text{ s}^2 \cdot 1 / v(2 \cdot 2,3,57 - 1) = 842 \text{ kN} / 2,48 = 340 \text{ kN}\]

- **PEEK:**
  \[F_{\text{max}} = 842 \text{ kN} / v(2 \cdot 1,44 - 1) = 842 \text{ kN} / 1,88 = 448 \text{ kN}\]

- **PA66:**
  \[F_{\text{max}} = 842 \text{ kN} / v(2 \cdot 1,16 - 1) = 842 \text{ kN} / 1,32 = 638 \text{ kN}\]

- **Kevlar carbon fibre and spectra polyethylene:**
  \[F_{\text{max}} = 842 \text{ kN} / v(2 \cdot 1 - 1) = 842 \text{ kN}\]

Ductility proves to have positive influence on the materials. However, there should be said that most of these values are assumed (M. Ashby et al., p. 113). The elongation in the material properties lists show that the elongation (ductility) is high enough (see image 15). The exact value is hard to define, because the bending starts and ends gradually. The kevlar carbon fibre and spectra polyethylene show less ductility. They have an elongation above 2% so they are not brittle. Their yield strength and tensile strength though is that high, that they will not reach the point of deformation easily.

Roughly most of the properties have been looked at. The only properties that are not being analysed are the architectural properties of the materials. There is not much information on CES on the appearance. PAI, PEEK, PA66 and Kevlar Carbon Fibre can only be opaque (non-transparent), Spectra Fibre is transparent (tinted transparent). There is not much more information about the architectural properties, like texture or colour in the program. More information should then be got out of examples and photos of already produced items and buildings.

One last property that may be considered is the price. This is no main property, simply because this project is a graduation project and not a real-life project. During studies is the only time to investigate the possibilities that are normally rendered impossible or too expensive. But to round up the story I will give a small summary of the costs. The material price can be decisive, when all other properties still don’t lead to a final material. The prices mentioned don’t include the final shaping and processing costs (Mike Ashby, 2016).

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost (EUR/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAI (30% glass fibre)</td>
<td>27,8 - 41,2</td>
</tr>
<tr>
<td>PEEK (30% carbon fibre)</td>
<td>68 – 74,2</td>
</tr>
<tr>
<td>PA66 (30% carbon fibre)</td>
<td>8,66 – 10,7</td>
</tr>
<tr>
<td>Kevlar 29 aramid carbon fibre</td>
<td>22,4 -37,4</td>
</tr>
<tr>
<td>Spectra 900 polyethylene</td>
<td>77,9 - 131</td>
</tr>
</tbody>
</table>

*Table 14: Prices per kilogram.*