

Reinforcement Toolbox, a Parametric Reinforcement Modelling Tool for Curved Surface Structures

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Summary: This paper presents a computational strategy and parametric modelling toolbox which aim at enhancing the design- and production process of reinforcement in freeform curved surface structures. The computational strategy encompasses the necessary steps of raising an architectural curved surface model of a concrete building to production level in terms of reinforcement. The Reinforcement Toolbox supports this strategy by offering structural engineers and other professionals in the building industry the functionality to create digital reinforcement models for curved surface structures.

Keywords: *Reinforcement; Complex geometry; Curved surface structures; Toolbox; Software development; Rhino; Grasshopper*

1. INTRODUCTION

Recent years have witnessed the realization of multiple concrete curved surface structures. The complex geometry of these structures led to new challenges in the design and construction of the reinforcement, see Figure 1.



Fig. 1: Complex curved reinforcement under construction at the first phase of the NSP Arnhem.

For a long time designers taking the lead in these types of structures were engineer-designers-builders like Felix Candela, Eduardo Torroja, Antoni Gaudí and Heinz Isler. Structural behaviour and constructability formed the main input for their designs. The current tendency to favour a more sculptural approach can lead to structurally less efficient shapes where high amounts of irregular curvature lead the geometry away from the line thrust. In case of concrete curved surface structures, shell action is then combined with significant bending action, which results in large amounts of reinforcement.

The complex geometry of the reinforcement generally leads to higher design and production costs. In order to check the design and reduce the risks of construction errors various strategies to verify the quality of reinforcement details have been adopted. The design of the reinforcement for the EPFL Learning Center for instance relied on digital 3D reinforcement models in combination with physical mock-ups [7]. Drawbacks of this strategy are the labour intensity and relatively high costs involved. A cost-effective strategy for designing reinforcement in curved surface structures does not yet seem to exist.

Currently reinforcement modelling software is not capable to properly deal with NURBS curves and surfaces, which renders the structural engineer less effective in designing their reinforcement. It can lead to missing out on design potential through ill-informed decisions, and makes that reinforcement design for curved surface structures cannot benefit from the advancements made in the field of BIM [3].

The computational strategy presented in this paper aims at enhancing the design and production process of reinforcement in curved surface structures. In support of this strategy Reinforcement Toolbox has been developed which enables structural engineers to create digital 3D reinforcement models for concrete curved surface structures, an example of such a model is shown in Figure 2.

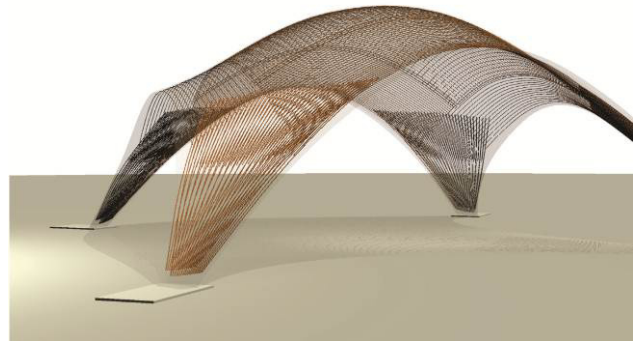


Fig. 2: Example of a 3D reinforcement model of a typical Isler shell created using the Reinforcement Toolbox.

2. IMPROVING THE REINFORCEMENT DESIGN PROCESS

2.1. Reinforcement Design Process

The reinforcement design process of curved surface structures is characterized by close cooperation between design and production industries. Primary stakeholders are the structural engineer, draftsman, contractor and the fabricator. Transfer of reinforcement information between those stakeholders during the design process relies on the exchange of reinforcement documents with specific sign conventions. This document flow, shown in Figure 3, has a clear direction, and contains progressively more detailed information moving towards the production and placement of reinforcement on-site.

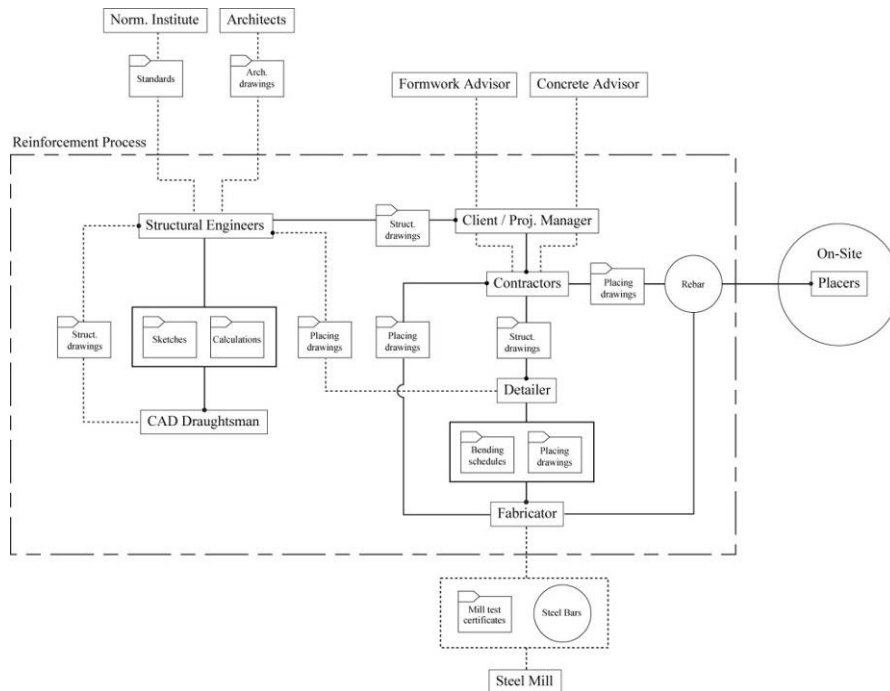


Fig. 3. The document flow associated to the reinforcement design process.

Four types of reinforcement documents are distinguished: reinforcement sketches; structural drawings; placement drawings and bending schedules. Each one is specifically adapted to a part of the design or production process.

The structural engineer produces a set of sketches based on his calculations, which are developed into a set of 2D structural drawings by a CAD draftsman. This internal communication loop will reiterate until the desired result is achieved. Structural drawings are passed via the client to the contractor who subcontracts the work to a reinforcement fabricator. Reinforcement detailers, who are either employed by the contractor or the fabricator, produce the bending schedules and placing drawings. The bend rebar are usually delivered on site by the fabricator.

2.2. 3D Reinforcement Models

Drawings involved in the current reinforcement process, both internal and external, are for the largest part 2D plans and elevations. The computational strategy envisions these will eventually be replaced with one single 3D model which contains all the relevant information. Using 3D reinforcement drawings can greatly improve the communication between stakeholders and thus improve the quality of data involved.

This becomes even more relevant when dealing with geometrically complex structures.

Having all the relevant information in one single 3D model which can be shared between the different stakeholders throughout the entire design process can significantly improve communications. It asks for an adaptation of the document flow, incorporating 3D drawings, see Figure 4.

3. THE COMPUTATIONAL STRATEGY

3.1. Three Important Design Aspects

The reinforcement design process is governed by three important design aspects:

- Geometrical control, the ability to unambiguously capture, manipulate and extract geometrical data from a 3D shape.
- Structural analysis: predicting the anticipated structural behaviour of concrete curved surface structures.
- Production: the possibilities of fabricators and placers to bring reinforcement into shape.

These are points of attention during any regular design processes, but become even more demanding when the geometry of the design is of a higher complexity. They form important input for the development of the computational strategy and are briefly discussed below.

3.1.1. Geometrical Control

Geometrical control plays a vital role in the design of reinforcement for complex curved surface structures, and forms the basis to other design aspects like structural analysis and production.

There are several practical reasons for wanting to design reinforcement in 3D. Compared to 2D drawings, 3D drawings are easier to understand and convey information in a less ambiguous way [2]. Straightforward reinforcement configurations, like beams and slabs, can easily be communicated through a limited number of sections and elevations. This doesn't hold for curved surface structures, as regular 2D representation is usually inadequate to transfer the full complexity of the design.

Successfully deploying a 3D reinforcement model for production purposes relies heavily on dimensional accuracy. In order to prevent non-fitting reinforcement bars on site, a well-defined reinforcement model starts with an accurate description of the concrete geometry. Current reinforcement software is unable to describe complex curved surface geometries. As part of the computational strategy a concept has been developed called 'The Solid Model', see Figure 5. This geometrical data structure enables the description of a continuous curved surface structure of varying curvature and thickness.

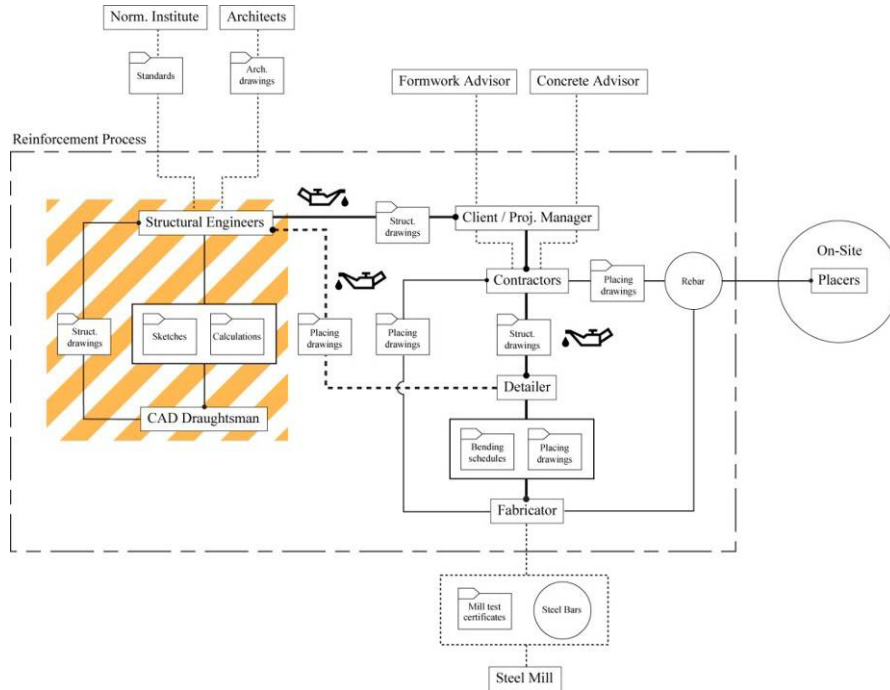


Fig. 4. Using 3D reinforcement drawings helps to improve communications between the different stakeholders.

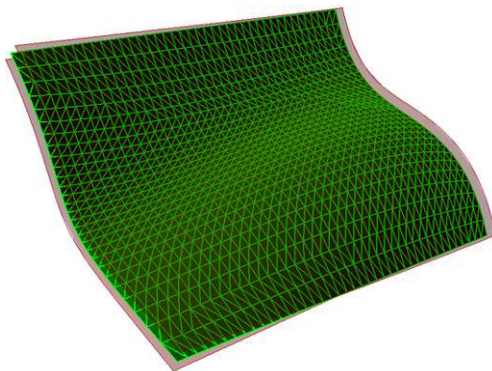


Fig. 5. Example of a Solid Model of a continuous curved surface structure of varying curvature and thickness.

3.1.2. Structural Analysis

The structural engineer needs to assign correct amounts, position and direction of reinforcement based on a thorough understanding of the structural behaviour and stress distribution in the curved surface structure. This is usually accomplished through a combination of structural rationalization based on first principles and FEM Analysis.

Structural analysis of concrete curved surface structures is particularly difficult as two different deformation modes, being membrane- and bending deformation, come together. Doing this on the basis of first principles alone is not enough, and FEM analysis is used to complement this information. FEM analysis software is an important tool for structural analysis of concrete curved surface structures, and it is incorporated in the strategy to visually convey information on direction and quantity of reinforcement, see Figure 6. From the Solid Model, which captures the geometry of the curved surface structure, a calculation mesh can be extracted, which ensures that the analysis model and the geometry used for reinforcement modelling directly match.

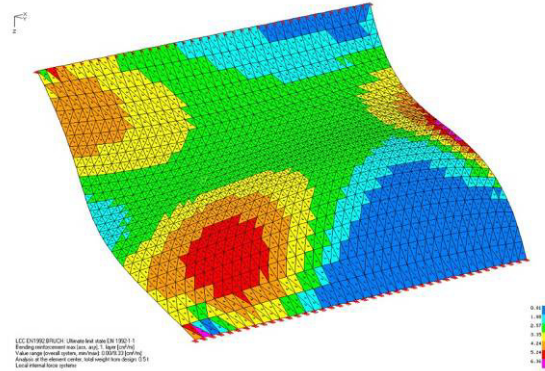


Fig. 6. FEM Analysis results

3.1.3. Production

During design stages the structural engineer translates structural analysis results into practical reinforcement configurations which comply with production standards. Reinforcement bars are brought into shape, suitable for fixing into concrete formwork, through a subsequent process of cutting and bending. They can either be delivered on site as pre-bent bars, or straight bars which are then brought into shape. Bending bars on site is practically unrestricted in terms of possible shapes, this way of working however is very labour intensive and costly. The computational strategy relies on prefabrication and is therefore bound by the production possibilities of bending machines.

The computational strategy incorporates a concept called 'Rebar DNA' which takes into account the aspect of production. It entails that Reinforcement bars are represented as a sequence of segments with constant or zero curvature, bent in plane. It allows for the approximation of curves with discontinuous curvature by a sequence of continuously curved segments with G1 continuity [5], see Figure 7.

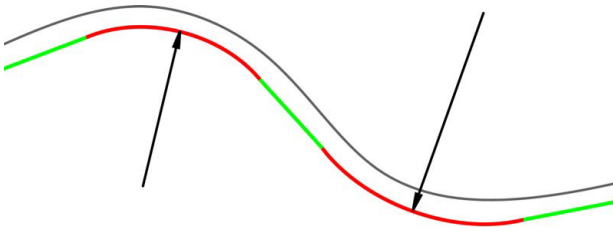


Fig. 7. Rebar DNA, a sequence of curves with zero or continuous curvature approximates a curve with varying curvature.

3.2. Computational Design Strategy

The strategy proposes a way of improving the design process of reinforcement in curved surface structures. It includes all necessary steps of raising an architectural curved surface model to production level in terms of reinforcement, see Figure 8.

Starting point of the strategy is a digital 3D curved surface model of the structure (a), commonly supplied by the architect. Surface rationalisation (b) through meshing is a proven technique which helps to gain control over the geometry of curved surfaces [6]. The Solid Model can be considered as the digital representation of the concrete volume in which the reinforcement is modelled (c). From the Solid Model a FEM mesh can be extracted, which offers the advantage of being able to directly project FEM Analysis results on the SolidModel (d). The visualisation of principle stresses and required amount of reinforcing steel in combination with reinforcement modelling functionality hands the structural engineer a powerful tool for the allocation of reinforcement (e). The digital reinforcement model (f) shows the actual reinforcement model and gives feedback on possible clashes. This cyclical design process can have multiple iterations until a satisfactory reinforcement model is achieved. Providing for a direct link between the reinforcement model and production facilities (g) finalizes the computational design strategy. It optimizes the document flow between the structural engineer and the fabricator, and hints at the possible production automation of complex reinforcement.

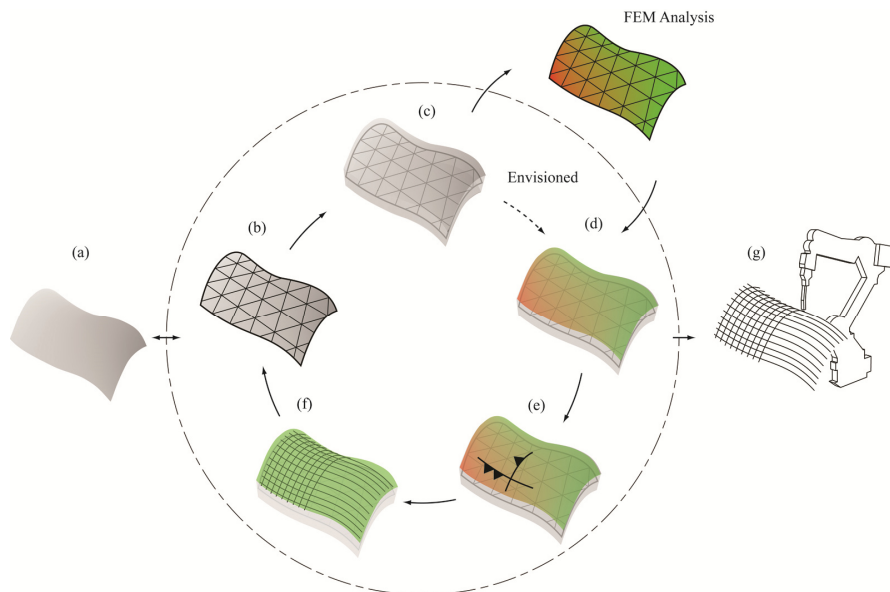


Fig. 8. Subsequent steps of the computational strategy: (a) Input of a curved surface (b) Surface rationalisation (c) Creation of the SolidModel (d) Visualization of FEM Analysis results (e) Allocation of reinforcement (f) Reinforcement model (g) Production.

3.3. Implementation of the Strategy

Bringing together the design tools for reinforcement in curved surface structures in a single 3D modelling environment as depicted in Figure 9, is an important step towards a more optimized design process. However, not all conventional tools are yet applicable to curved surface structures. The three concepts within the computational design strategy help to overcome this deficiency.

The computational strategy proposes a way of progressing reinforcement for curved surface structures from design to production. A direct link between the reinforcement CAD model, FEM analysis and production tools in a singular 3D modelling environment offers users the possibility to quickly research the structural implications of a reinforcement design.



Fig. 9. Bringing together the separate tools used in the reinforcement process into one multi-functional 3D design environment.

Bringing the disciplines closer together through a computational design tool has multiple advantages: a reduced risk of mistakes due to data loss at the interfaces between stakeholders, and a more optimized design process, by bringing together the driving design factors, and migrating knowledge of production to earlier design stages. To facilitate this process a software toolbox has been developed which allows professional users to apply the computational strategy to reinforcement design for curved surface structures.

4. THE REINFORCEMENT TOOLBOX

A first version of the Reinforcement Toolbox has been developed, and serves as a proof of concept to the computational strategy. It offers professional users a tool which can be used to control the design aspects of reinforcement in curved surface structures.

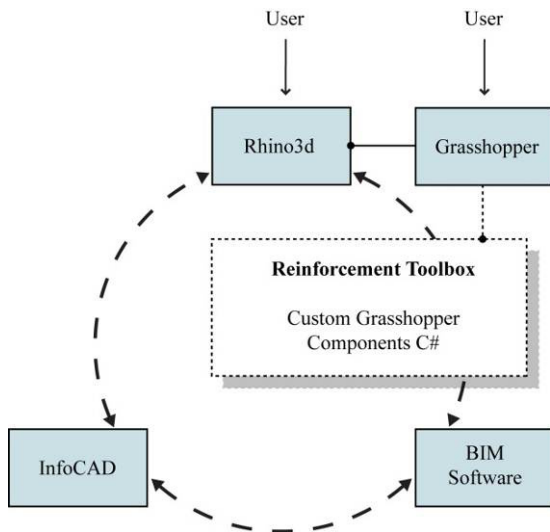


Fig. 10: The Reinforcement Toolbox functions as an interacting overlay on top of existing systems.

4.1. System Architecture

The system architecture of the Reinforcement Toolbox, Figure 10, is developed with strong attention to the multifaceted design process of reinforcement in curved surface structures, and enables users to perform various operations at their own discretion. It builds on existing platforms and consists of custom components.

The Reinforcement Toolbox has been developed using Microsoft Visual Studio 2008 and written in the C# programming language. RhinoCommon, a .NET plug-in SDK which can be used across all Rhino platforms [4], enables developers to extend Rhino's functionality by creating Rhino plug-ins. Grasshopper, in turn a .NET plugin for Rhino, is a parametric platform which connects to Rhino's extensive geometrical library. The Reinforcement Toolbox consists of a collection of custom Grasshopper components each providing for a demarcated portion of the functionality.

4.2. Components

The Reinforcement Toolbox components are categorized according to four sub-categories: Conditions; Geometry; Reinforcement and Post-Processing. For the first version of the Reinforcement Toolbox several components have been developed, see Figure 11. Together they offer the necessary functionality for a structural engineer or CAD draftsman to design longitudinal reinforcement groups and reinforcement meshes for curved surface structures.

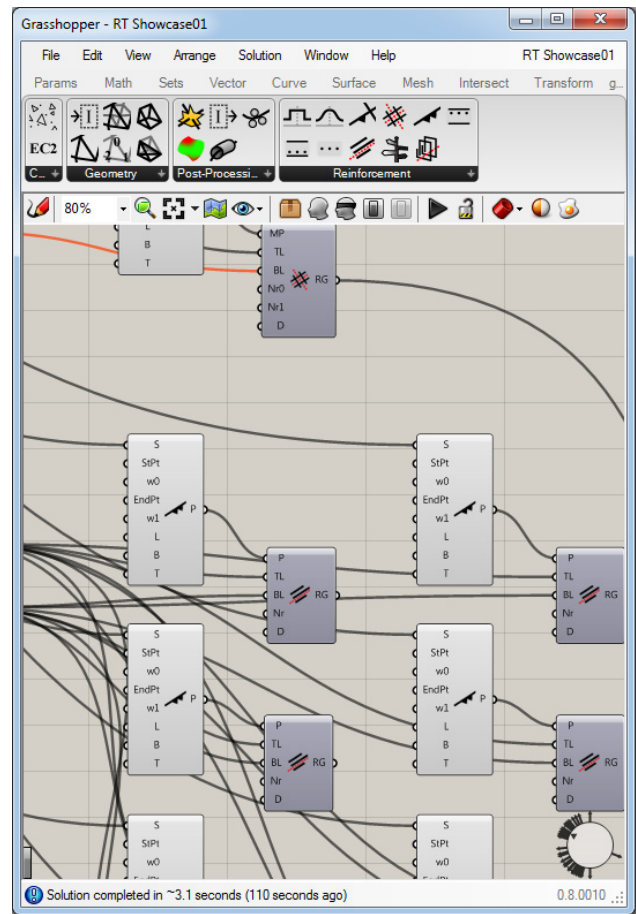


Fig. 11: Screenshot showing a typical reinforcement toolbox configuration.

4.3. How the Toolbox Works

At the heart of the Toolbox lie three key components: the SolidModel component, the Path component and the Allocator component. For creating the reference mesh, the Toolbox relies on existing mesh functionality either in Rhino or FEM analysis software. Figure 12 gives a six step explanation in of how reinforcement is created.

In a first step the averaged normal vectors of adjacent faces are created in the vertices of the reference mesh. These are used in a second step for creating the Solid Model. A third step involves a start- and endpoint being assigned by the user, creating a so-called Rebar Path. In the fourth step the Path Points are determined through an algorithm which finds the plane edge intersection between the reference mesh edges and the y,z-plane of the Rebar Path. The last two steps are dominated by the Allocator component which assigns the Path Points to the correct offset layer within the Solid Model. Each Path Point has a pointer to the reference mesh face which contains it, together with the u,v-coordinates which determine its position. The Allocator component uses this information when it creates a RebarPoint: a temporary offset face within the Solid is created on which the RebarPoint is plotted. A Rebar object contains multiple of these RebarPoints, together they form the control points of a smooth center line which defines the Rebar.

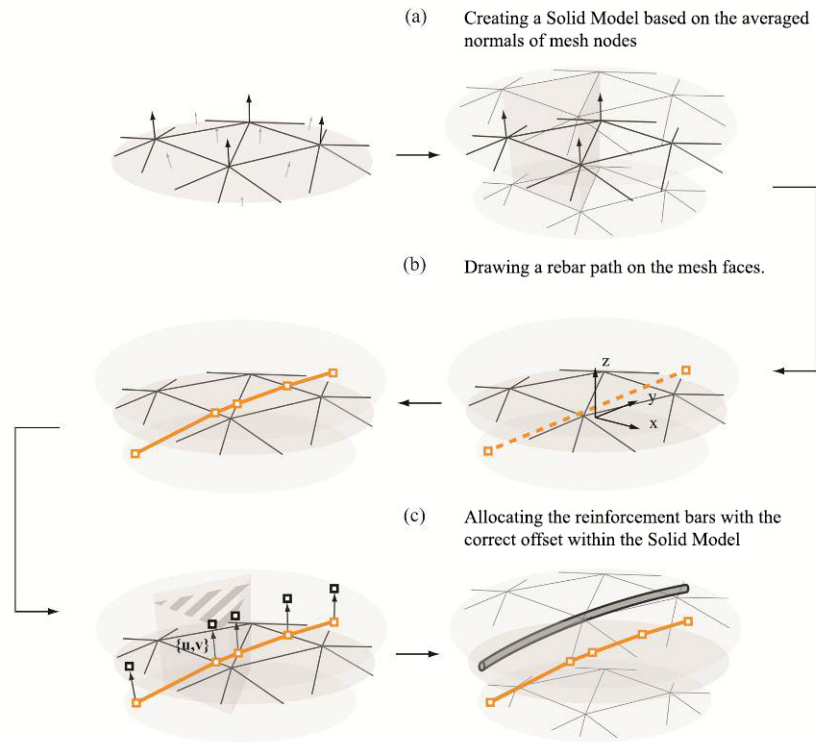


Fig. 12. The workings of the Toolbox explained according to three key components, (a) the Solid Model component, (b) the Path component and (c) the Allocator component.

5. RESULTS

The reinforcement Toolbox has been applied to a curved surface geometry with a variable cross-section and double curvature, see Figure 13. The reinforcement model consists of a top and bottom reinforcement

mesh, together with three groups of longitudinal reinforcement bars. They are placed according to the indicated amount of reinforcement and load paths.

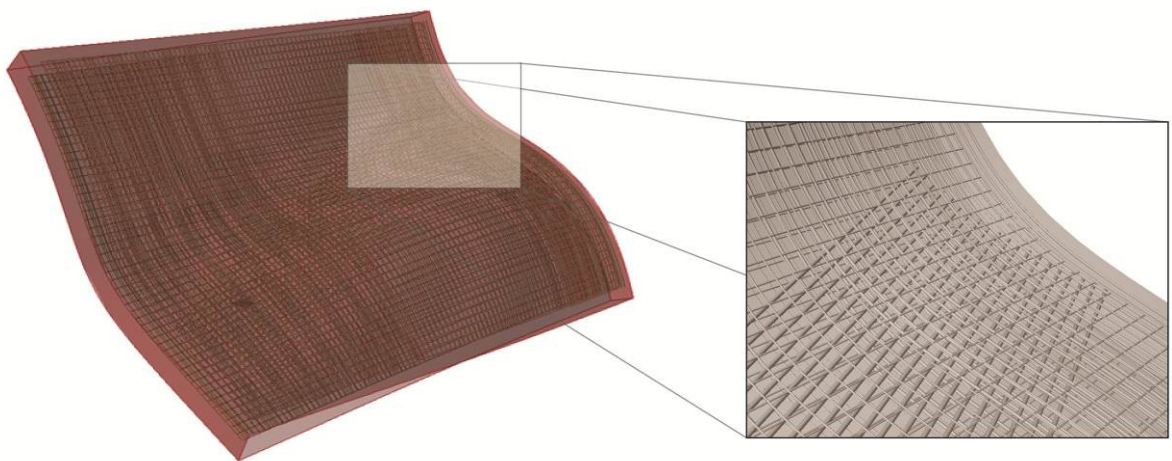


Fig. 13. A reinforcement model for a curved surface structure created using the Reinforcement Toolbox.

The results of the FEM Analysis are visualised using the Reinforcement Toolbox, see Figure 14. Principle stress trajectories (n1, n2) indicate the flow of forces through the structure. This information, combined with

the required amount of reinforcement, assists the user of the Toolbox with the design of reinforcement. The created reinforcement model is compared to the required amount of reinforcement as indicated by InfoCAD, and the results are fed back to the user, see Figure 15. The

Reinforcement Toolbox can be used to create longitudinal reinforcement groups or reinforcement meshes for both curved as well as planar geometry. It verifies created reinforcement models in accordance to the

assigned building standard; if the reinforcement model doesn't comply the user gets notified.

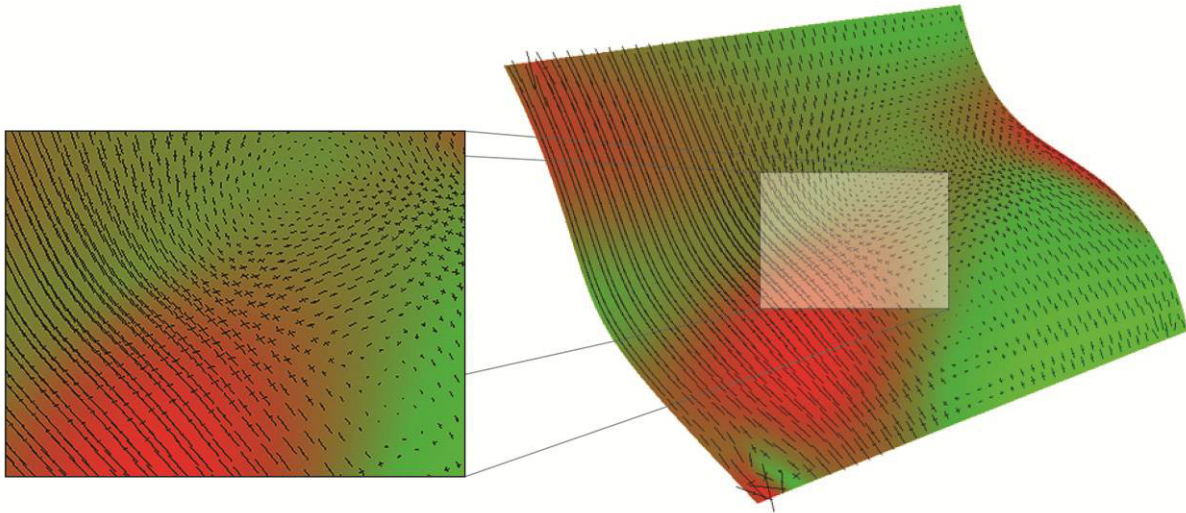


Fig. 14. The Reinforcement Toolbox is used to visualise FEM Analysis results: required amount of reinforcement and principle stresses $n1$ and $n2$.

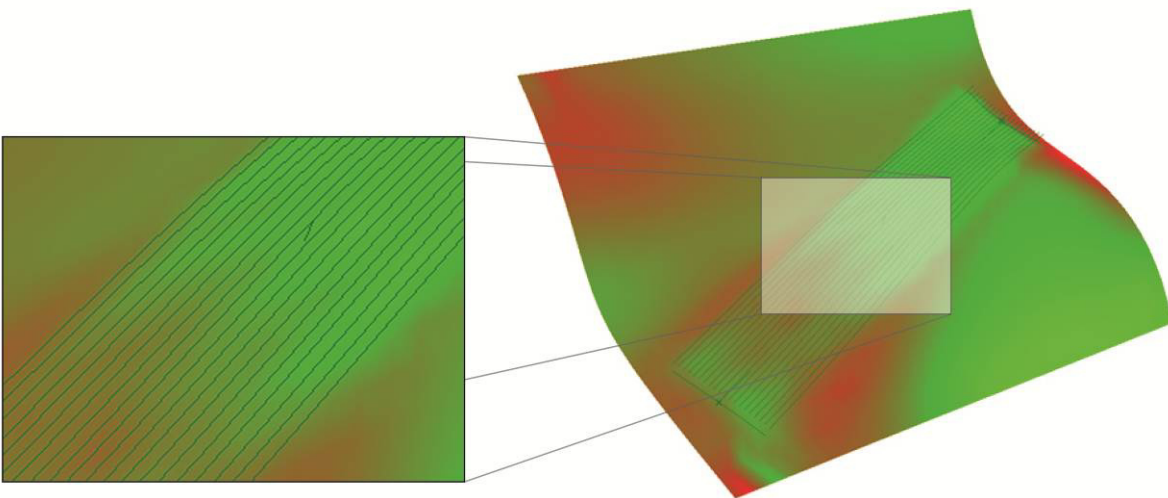


Fig. 15. The Reinforcement Toolbox provides feedback on how the modelled reinforcement relates to the required amount as indicated by the FEM Analysis. The image shows the centre lines of a group of reinforcement bars.

6. DISCUSSION

The computational strategy proposes a way of improving the design process of reinforcement in curved surface structures. A Reinforcement Toolbox has been developed as an initial proof of concept of this strategy. The vision is that it will be developed further into a mature application that can add real value to the reinforcement process.

During the development process of the Reinforcement Toolbox testing has been applied in various forms by using interactive debuggers, running the application to check its consistency, and creating output files. It has been tested on two crucial aspects, being the definition of the MeshTopology, which forms the basis of the SolidModel, and the

assigned concrete cover which is important for a proper reinforcement definition.

The MeshTopology is the topological structure which lies at the basis of any SolidModel. It establishes the relations between triangular mesh elements in a unified manner so that different meshes can serve as input to the SolidModel.

The reinforcement cover is directly assigned by the user and checked against the minimum cover c_{min} as prescribed by the Euro Code 2 [1] (EN1992-1-1:2004 table 4.3N). The recommended allowance in design for deviation, Δc_{dev} of 10 mm is maintained (EN1992-1-1:2004 Section 4.4.1.3). The maximum allowed deviation compared to the nominal

cover c_{nom} is determined to an absolute deviation of 5mm. The validation of the cover has been checked against this threshold.

Distance of individual RebarPoints and curves has been measured using a straightforward Grasshopper definition, applying the 'ClosestPoint' and 'Distance' components. The resulting output, a list with distances has been exported to Excel, where it is automatically checked for compliance with the assigned cover.

Deviations in the RebarPoint cover have two reasons. The first reason is the inaccuracy introduced by the surface rationalisation. A mesh is never hundred per cent accurate in approaching a curved surface. The second reason is the way points are allocated within the Solids. Through different directions in the average vectors at the vertices deviations occur when creating an offset layer. The magnitude of this type of inaccuracy increases with increasing curvature.

Although inaccuracies exist they are of minor scale and magnitude and fall within the set threshold of 5mm. Measurements like mesh refinement can be taken to improve the accuracy of the reinforcement models.

7. CONCLUSIONS

Research into the reinforcement process of curved surface structures has revealed the need for new strategies to create digital reinforcement models. With engineering tools shifting more and more towards the digital domain, computational tool development has become a viable approach for enhancing the structural design process.

The Reinforcement Toolbox can be applied to both complex curved surface structures as well as non-complex structures, making it a widely applicable design tool. Users can apply the Reinforcement Toolbox at their own discretion within any given stage of the reinforcement process either to quickly research different reinforcement design alternatives, or use it to build extensive reinforcement models. The parametric reinforcement models are easily adaptable to design changes, which makes them valuable throughout the entire reinforcement process. Validation of two important aspects of the solid- and reinforcement models created using the Toolbox, the mesh topology and concrete cover, revealed no inconsistencies or large deviations from the allowed tolerances.

The Toolbox has been designed considering user friendliness, and freedom of use. The modular setup allows users to combine components at their own discretion allowing for the intended freedom when designing reinforcement.

8. REFERENCES

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