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Topology optimizazion of gridshells with reused elements

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Abstract

The concept of reusing structural components is receiving increasing attention from researchers and industry professionals. Indeed, by incorporating reclaimed elements from demolished buildings, new structures gain added value in terms of reduction of costs and, moreover, environmental impact. Steel elements are particularly well-suited to this goal because they retain their mechanical properties over time. In this context, the paper presents a novel design approach for gridshell structures based on an advanced topology optimization technique specifically tailored for incorporating reused elements. The approach is applied to a case study derived from literature by considering different scenarios in terms of stocks of reusable elements. The obtained solutions, and the comparison among them, highlight the significant impact of the characteristics of reusable elements stock on the final solution. Moreover, it also emerges the important role of the proposed approach as a valuable tool for selecting ad-hoc stocks of reusable elements for obtaining gridshell structures that meet structural requirements while offering significant cost and environmental benefits.

Keywords: gridshell; topology optimization; size optimization; FreeGrid Benchmark; gridshell; reused elements

1. Introduction

The construction industry faces a critical challenge: its significant environmental impact due to high resource consumption (materials and energy). To address this, the industry is actively seeking ways to reduce its environmental impact. This includes exploring more efficient design solutions and innovative construction procedures that promote sustainability. In this context, steel structures are particularly well-suited for this approach, as their material properties remain strong over time. This aligns perfectly with the growing interest in structural component reuse, as evidenced by recent research.

Among these, Brütting et al. [1]–[3] explored various design strategies and applications for reusing elements and joint connections. These studies include: a design strategy for reticular structures using a limited stock of elements and joints derived from disassembly different structural typologies (gridshell, portal frame, column); a design optimization procedure for a roof truss station utilizing elements from dismantled transmission towers; the design of a frame structure using elements from dismantled buildings. For all the applications the authors particularly emphasized the benefits reached in terms of reduction in greenhouse gas emissions.

While reuse has a long history in structural engineering, its systematic application offers significant potential for environmental impact reduction. However, a gap exists in expertise and design tools specifically tailored for reuse, delaying its broader adoption [4].

In particular, although recent research has explored innovative design approaches for gridshells that combine sizing and topology optimization [5]–[9], there remains a lack of contributions focusing on optimization strategies specifically tailored for designing gridshells that incorporate reused elements.

This paper presents a novel approach for optimizing steel gridshells that integrates reclaimed members into the structure. The approach effectively combines topology and size optimization techniques through a unique process using genetic algorithms, and its validity is demonstrated thought its application to a case study derived from the literature and considering different scenarios for available stocks of reusable elements. The results clearly demonstrate the proposed approach's ability to provide lighter solutions, which translates to low-cost and a reduced environmental impact. This is achieved by its ability to simultaneously optimize both the grid configuration and the placement of reused members.

The proposed approach has been applied to one of the gridshell cases within the FreeGrid Benchmark [10], [11]: the barrel vault. In particular, different scenarios in terms of stocks of possible reusable elements have been considered for analyzing the influence of the characteristics of the elements composing the stock on the optimization process of gridshells.

2. Proposed approach

The aim of the proposed approach is to implement a procedure that integrates topology and sizing optimization for the optimal design of gridshell structures, incorporating members derived from decommissioned structures (referred to hereafter as reused members). Then, as detailed in the following sections, the quantity (i.e. the number N), length, and cross-sectional dimensions of reused members constitute new input data to be introduced into the optimization process.

A schematic representation of this procedure is provided in Figure 1.

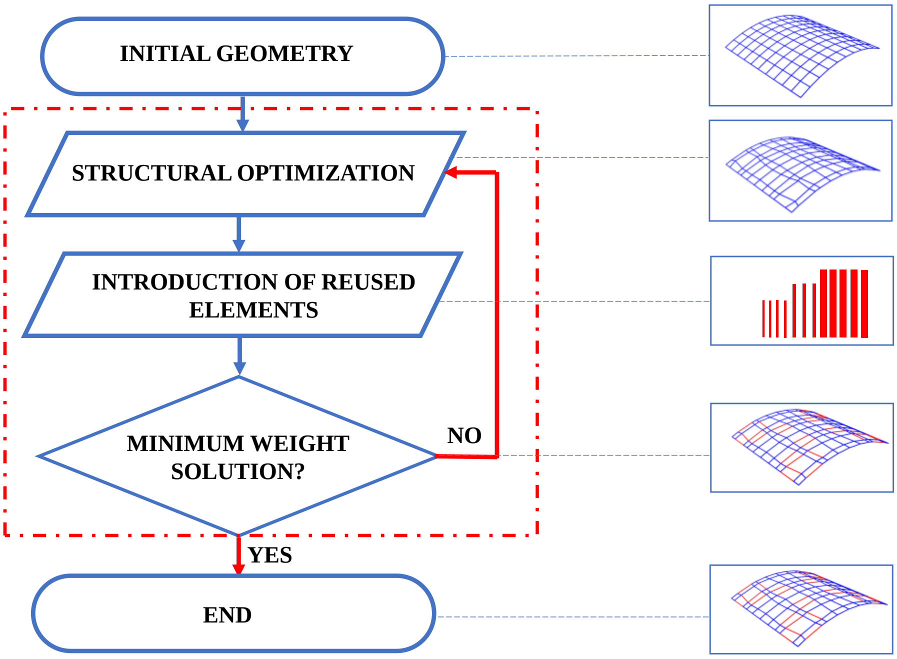

Figure 1. Proposed procedure for topology optimization of gridshells with reused components.

Considering a fixed shape of the surface characterizing the gridshell and a predefined number of quadrangular elements composing the mesh (and then, a fixed number of joints of the mesh), the procedure iteratively generates grid solutions by moving the joints along the gridshell surface. For each solution, a custom subroutine compares the lengths of the elements of the grid with the lengths of the reused elements. Then, considering the elements of the grid with length similar to the one of the reused members, the subroutine strategically adjusts the corresponding joints to accommodate into the grid the reused elements. Following the joint adjustments, the solution incorporating reused members undergoes structural analysis to design the cross section of new members only. An optimization process is then performed with the goal of minimizing the weight of new designed members (W_New) while respecting constraint conditions imposed on: maximum utilization ratio (Umax, i.e. Demand to Capacity ratio), maximum displacement (Dmax), and buckling factor (BF, i.e. the ratio between the buckling load and the applied load), the latter obtained from a linear buckling analysis.

3. Case study

To validate the proposed approach, we consider one of the three gridshells from the FreeGrid Benchmark by Bruno et al. [10], [11]. Specifically, the accounted case study focuses on the barrel vault. It is characterized by a parabolic generatrix with a span B=30 m and a rise f=B/8, plan dimensions are $B \times L^*$, where L^* is equal to the length of the generatrix, and a mesh composed of 20x20 quadrangular elements. All the members are made of steel S355, with a pipe cross-section of diameter ϕ 139 mm and a thickness t of 14.2 mm, then a ratio $\phi/t=9.79$.

For this case study, the authors introduce some simplifications to streamline the analysis: the symmetric load condition only; all edges constrained; a discretization of 10x10 quadrangular elements; no imperfections. Although the presence of different load conditions (both symmetric and asymmetric) and imperfections can affect the solutions in terms of topology and cross-section sizing, these aspects have not been considered in the design of the selected case study for the sake of simplicity. The objective is to demonstrate the potential of the proposed tool in designing gridshells with reused elements. Nevertheless, these aspects can certainly be implemented within the framework of the proposed approach..

Furthermore, during the structural design of cross section of new members, the pipe cross-section is considered by varying the diameter while keeping constant the ratio ϕ/t, following the benchmark specifications (Figure 2).

3.1 Preliminary analyses

Before applying the proposed approach to the selected case study, preliminary analyses were carried out to deduce reference cases.

For both the baseline 20x20 regular gridshell (Figure 3a) and the simplified 10x10 grid (Figure 3b), preliminary analyses were conducted using a static linear analysis. All members were assigned the cross-section dimensions specified in the benchmark. The analyses evaluated the following parameters: weight, maximum utilization ratio (U_{max}), displacement ratio (Δ), defined as the ratio between the maximum dispacement D_{max} and the limit one D_{lim} imposed as the span B over 250, and buckling factor (BF).

Additionally, considering the simplified 10x10 grid, a member cross-section optimization was also performed (solution called 10x10_opt; see Figure 4). This optimization varied the external diameter of the pipe sections (while maintaining the benchmark's ϕ/t ratio) to minimize weight while adhering to the following constraints: $U_{max} \leq 1$; $\Delta \leq 1$; $BF \geq 1$.

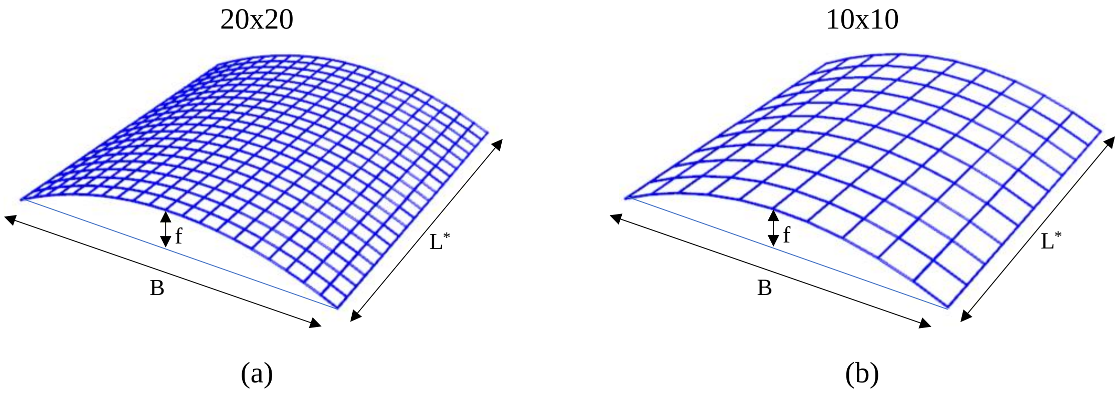

Figure 3. (a) Geometry of gridshell with a 20x20 mesh (BaseLine) and (b) 10x10 mesh.

Figure 4 summarizes the key findings from the preliminary analyses. It plots the weight (W_new), maximum utilization ratio (U_{max}), displacement ratio (Δ), and buckling factor (BF) for all three configurations: the baseline 20x20 gridshell, the simplified 10x10 grid, and the optimized 10x10_opt grid. As expected, both the 10x10 and 10x10_opt solutions achieve significant weight reduction compared to the 20x20 grid. Notably, the optimized 10x10_opt configuration achieves the lowest weight among all three.

In terms of structural performances, the displacement ratio results significantly lower than the limit value for all cases, whilst U_{max} approaches the limit value for the 10x10_opt case, then by underlying for this case a more efficient material utilization. Differently, the BF significantly reduces from 20x20 to 10x10 and 10x10_opt solutions, but it remains above the safety limit.

The obtained 10x10_opt solution will be assumed in the following as the reference case to carry out considerations about the solutions including reused elements obtained from the proposed approach.

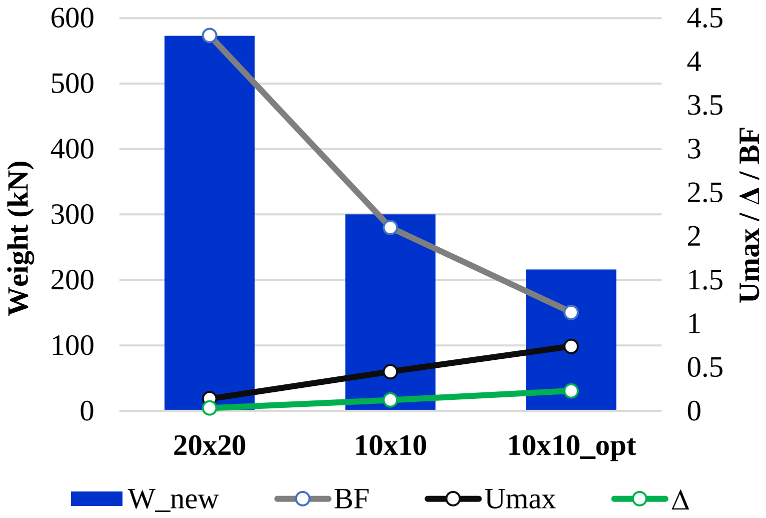

Figure 4. Results of preliminary analysis.

3.2 Application of the proposed approach

The proposed approach (Section 2) has been applied to the 10x10 mesh case, considering different scenarios in terms of stock of reused elements. These scenarios were deduced by varying the number (N) and length (L) of elements in the stock (here, N represents the reused elements to introduce into each quarter of the gridshell, due to the imposed double symmetry). Importantly, the cross-section shape (pipe), diameter (ϕ = 139 mm), and thickness (t = 14.2 mm) of the elements remained consistent with the benchmark.

In particular, the following five stock scenarios were considered:

- N=8 – L=4m;
- N=12 – L=4m;
- N=8 – L=5m;
- N=12 – L=5m;
- N=12 – L=4m (4 elements); L=4.5m (4 elements); L=5m (4 elements).

It can be observed that, while the first four stocks are composed of elements with the same length, the last stock accounts for elements with different length values.

Figure 4 illustrates the impact of reused element on the resulting grid topology and element arrangement. The figure shows the solutions obtained using the proposed approach, highlighting the positions of nodes (topology) and reused elements (red lines). We can clearly observe how the characteristics of the reused element stock (number, length) influence the final grid configuration, causing deviations from the original regular mesh (distortion).

Figure 6 summarizes key characteristics of the obtained solutions in terms of: weight of new (W_new) and reused (W_reused) members, Umax, Δ, and BF. It also includes the values of the 10x10_opt solution (i.e. the one characterized by a regular mesh and a cross-section of members deduced from a sizing optimization process) for comparison. From the figure it is possible to observe that:

- the total weight (weight of new + reused elements) of some scenarios is lower than the 10x10_opt solution, while others are heavier. Notably, among scenarios using elements of uniform length, increasing the number of elements in the stock (N) leads to a weight increase.
- The weight of new elements (W_new) in all scenarios is significantly lower (30% to 46%) compared to the 10x10_opt solution. In particular, the greatest reductions are achieved in scenarios with the longest elements.
- The maximum utilization ratio (Umax) is consistently high across all solutions, approaching the limit value. This is slightly higher compared to the 10x10_opt solution.
- Both the displacement ratio (Δ) and buckling factor (BF) show minimal variations across all obtained solutions and compared to the 10x10_opt solution.

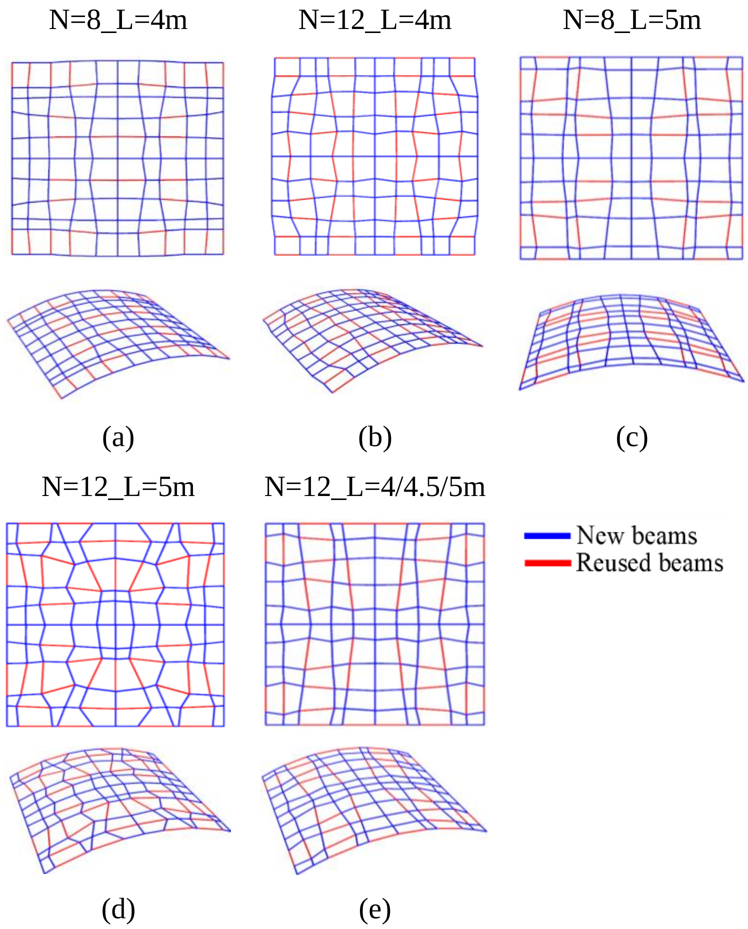

Figure 5. Topology and disposition of reused lements derived by the proposed approach.

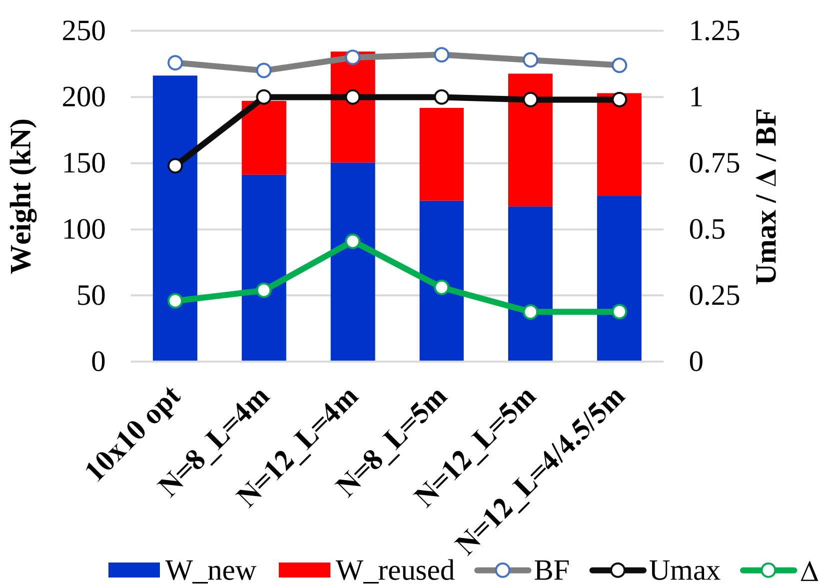

Figure 6. Results obtained by the proposed approach for different stocks.

4. Conclusions

This paper has presented a design tool for gridshell structures that incorporates elements with pre-defined cross-sections and lengths (representing a stock of possible reusable members). The tool is based on a topology optimization process to minimize the weight of the new elements. This optimization adheres to pre-defined strength and stiffness requirements for the overall structure. To integrate reused elements, the tool utilizes a dedicated subroutine. This subroutine compares the lengths of elements identified by the optimization process with the available reused element lengths. It then selects the closest matching reused elements and refines the nodal coordinates to accommodate their specific lengths.

The approach has been applied to the barrel vault case deduced from the FreeGrid benchmark [10], [11]. In particular, different stocks scenarios composed of different number of reused elements with different lengths have been considered.

The results highlight the significant impact of reused element stock characteristics on optimized gridshell solutions. Particularly, both the length and number of reused elements strongly influence the structural performance and weight of the gridshells.

The above outcomes underline the role of the proposed approach as a valuable tool for selecting ad-hoc stocks of reusable elements for obtaining gridshell structures that meet structural requirements while offering significant cost and environmental benefits.

Future developments will concern the influence of reused element cross-section dimensions, currently assumed to be uniform within each stock. Additionally, we will investigate the application of this approach to scenarios deduced from stock configurations derived from real demolished structures.

Acknowledgements

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