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FreeGrid benchmark: focusing on sustainability for overall performance enhancement of gridshells

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Abstract

FreeGrid (https://sites.google.com/view/freegrid/home) is a benchmark on free-edge steel gridshells, aimed at gathering researchers, designers, consulting engineers, architects, builders, to discuss common design case studies and compare methods, approaches and solutions for the design and optimization of gridshells. For this aim, a methodological framework has been set up for the holistic assessment of the overall performance of proposed design solutions. In particular, considering the intrinsic multidisciplinarity of the gridshell design problem, the overall performance indicator is defined as a linear combination of three partial performance metrics, quantitatively accounting for structural response, buildability and sustainability. This study strives to achieve a good level of overall performance for one of the gridshell case studies by mainly focusing on the sustainability aspects. A crucial design choice toward sustainability is here made, namely the use of members for the structural patterns reclaimed from dismantled structures. This overwhelming choice strongly affects the optimization problem since its formulation, due to the limited stock of structural elements available. Some modifications are also suggested to both the proposed performance metrics and the method for a preliminary and simplified performance assessment of design solutions that reuse reclaimed elements.

Keywords: FreeGrid benchmark, gridshells, circular structural design, steel element reuse, design solutions, performance assessment, buildability, sustainability, optimization.

1. Introduction

The study presented in this paper approaches the structural design problem of gridshells through the lens of the steel reuse, and moves along the boundaries between two research contexts, i.e. the FreeGrid benchmark and the Re-Grid project.

Freegrid [1] is a benchmark on free-edge steel gridshells, aimed at gathering researchers, designers, consulting engineers, architects, builders, to tackle common design case studies and compare methods, approaches and solutions for the design and optimization of gridshells. For this aim, a methodological framework has been set up for the holistic assessment of the overall performance of proposed design solutions. In particular, considering the intrinsic multidisciplinarity of the gridshell design problem, the overall performance indicator is defined as a linear combination of three partial performance metrics, quantitatively accounting for structural response, buildability and sustainability.

The Re_Grid research project embraces the strategic theme of circular economy as applied to the construction industry sector, focusing on structural steelwork. The specific topic is the reuse, i.e. recover and reuse of structural elements or components coming from buildings, infrastructures, or constructions that have become obsolete or no more necessary. This approach is particularly suitable for steel structures, since steel is a long-lasting material and the steel structures are inherently discrete, thus can be easily disassembled, giving rise to stocks of elements to be reused. Within the research currently ongoing, the possibility of including reclaimed components into the optimal design of structures to reduce their environmental impact is investigated.

A gridshell, in particular the barrel vault suggested within the FreeGrid benchmark, is considered here as case study for the initial exploration of the reuse-based design problem starting from a stock of structural elements dismantled from their original structural systems. The idea is to strives to achieve a good level of overall performance for the gridshell (as computed according to [1-3]) by mainly focusing on the sustainability aspects. The design choice toward sustainability here made, i.e. the use of members salvaged from dismantled structures, is expected to reveal an overwhelming impact on the optimization problem, from the formulation to the outcomes.

In the following, some additional details are provided on the barrel vault, selected among the FreeGrid case studies, and then slightly modified to be used here as archetype. A stock of steel elements, properly generated, is considered as virtual inventory of available structural members, and some grid solutions for the barrel vault are proposed and discussed, together with some simplified assumptions, made in this initial phase of the research. Some modifications are also suggested to both the proposed performance metrics and the method for performance assessment for including design solutions that reuse reclaimed elements.

2. The Freegrid case study and the barrel vault archetypes

The FreeGrid barrel vault case study [1-3] is a single-layer gridshell with quadrangular mesh; set the geometry (without imperfections) and the pattern, as well as design constraints and load conditions, the steel structural members have been designed under the assumption of fully hinged boundary. This solution, provided in [1-3], is appointed as *Background Gridshells* (BGs). Then, designers and researcher willing to participating to the benchmark, are called to propose alternative design solutions for the barrel vault in the case of one free edge.

In this paper some additional BGs are firstly defined for the barrel vault; then, differently from FreeGrid, new design solutions are proposed for the fully constrained BGs by reusing steel members coming from a virtual stock of dismantled elements. The new design solutions proposed for the fully constrained BGs are appointed as *Reused-based Background Gridshell* (ReBG) solutions.

2.1. Barrel vault archetypes

Geometrical and structural characteristics of the barrel vault BGs are provided in Fig. 1. All BGs are characterized by the same shape, described by the following parabolic generatrix and directrix equations, respectively given by:

$$z = -\frac{x^2}{2B} + f, \quad A = B\left[\frac{\sqrt{5}}{4} + ln\left(\frac{1+\sqrt{5}}{2}\right)\right] \qquad \text{for } \left\{-\frac{B}{2} \le x \le \frac{B}{2}, y = 0\right\} \tag{1}$$

$$z = f \qquad \text{for } \left\{-\frac{L}{2} \le y \le \frac{L}{2}, x = 0\right\} \tag{2}$$

The geometry is defined by: B = 30 m, span length; A = 31.12 m, generatrix arc-length; $L = A$, length of the spring line; $f = B/8$ = 0.15 m, rise; $h = f$, maximum height above the horizontal reference plane. All internal joints of gridshells are rigid, while external joints are perfectly hinged along L lines and allow motion in y direction along the head arches. Two different Load Conditions LC_k (k = 1, 2) are adopted, i.e., a symmetric (LC_1) and an asymmetric (LC_2) load condition. In each LC_k the applied loads are the self-weight of structural members, g, the permanent weight of glass cladding, q_1, and the snow, q_2. At the Ultimate Limit State (ULS), q_1 = 600 N/m^2 and q_2 = 12000 N/m^2; at the Serviceability Limit State (SLS), q_1 = 400 N/m^2 and q_2 = 800 N/m^2. Both q_1 and q_2 are applied as point loads according to the following expressions: for LC_1, $Q_{1,j} = (q_1+q_2)\cdot s_j$ with s_j the projection on the horizontal plane of the tributary area of the j-th joint; for LC_2, $Q_{2,1,j} = q_1\cdot s_j$ and $Q_{2,2,j} = q_2\cdot s_j$.

BG solutions are characterized by steel structural members with the same properties and cross section as the ones assumed in FreeGrid: Young's Modulus, E = 210000 MPa, Poisson's ratio, υ = 0.3, yield strength, f_y = 355 MPa, density, ρ = 7850 kg/m^3, circular hollow section O 139.7 mm x 14.2 mm.

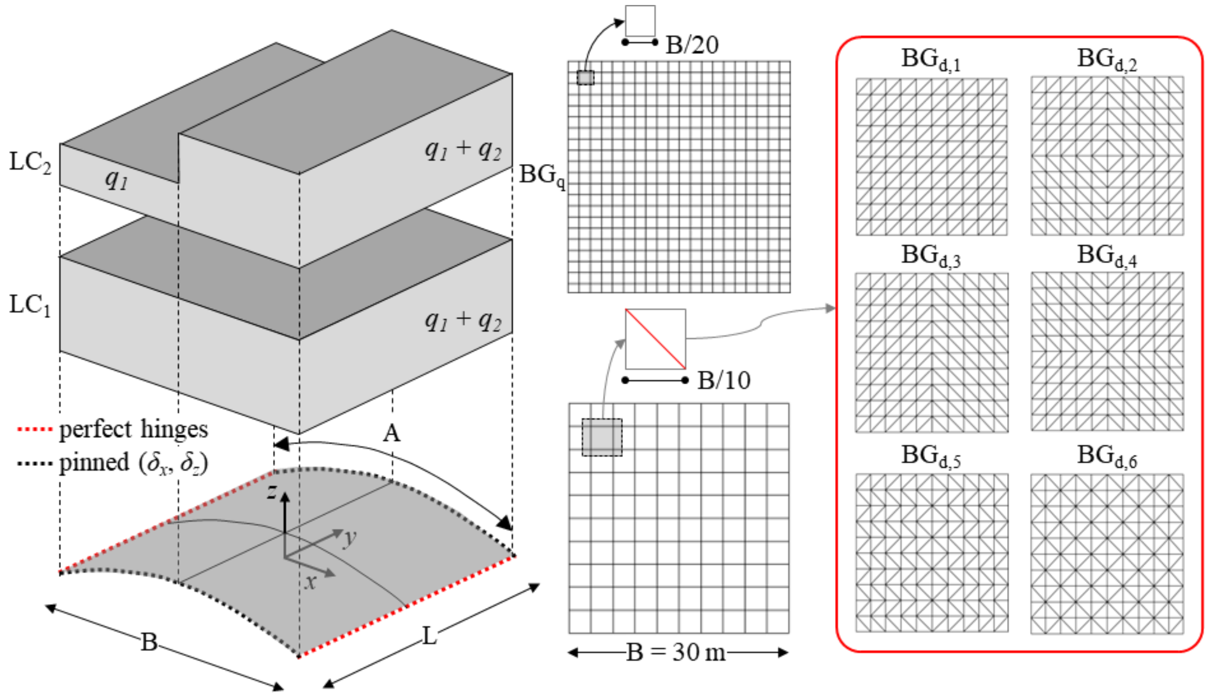

Figure 1: Main geometrical and structural features of the barrel vault BGs

Other than the BG solution adopted in FreeGrid, characterized by quadrangular meshes and here appointed as BG_q, six additional solutions with diagonalized meshes – with diagonals arranged in different manners – are here defined and appointed as BG_{di}, with i = 1, …, 6. In BG_q, the gridshell is discretized in 20 units along both x and y directions; therefore, each unit has dimension $B/20$ x $L/20$ ≈ 1.5 m x 1.56 m in the projected horizontal plan. In BG_{di}, the gridshell is discretized in 10 units along both x and y directions; therefore, each unit has dimension $B/10$ x $L/10$ ≈ 3.0 m x 3.11 m in the projected horizontal plan. For the sake of simplicity, the quadrangular unit is identified by the side of $B/20$ = 1.5 m and the diagonalized unit by the side of $B/10$ = 3.0 m in the following.

The geometrical and structural setup of the ReBG solutions is the same as BG counterparts with both quadrangular and diagonalized units. In ReBGs both new and reused steel elements are adopted, with circular hollow cross-sections. A virtual stock of 345 steel reclaimed members, summarized in Table 1, has been generated to simulate a realistic inventory of members cross sections and lengths. The stock is divided in 12 groups, with element lengths (l_{Re}) that vary from 1.80 m to 4.2 m and total number of elements (n_g) that varies between 15 and 40. All elements have circular sections with different diameter (Φ) and thickness (t). To account for material degradation, albeit in a very simplified way, S275 steel grade is assumed for reused elements instead of the S355 utilized for the new ones [4].

Table 1: Virtual stock of reclaimed steel members for barrel vault ReBGs

l_{Re} [m]	1.8	2	2.1	2.3	2.5	3	2.6	3.1	3.2	3.5	4	4.2
n_g [-]	40	25	30	25	30	25	40	30	15	20	25	40
Φ [mm]	180	120	180	150	200	150	200	150	150	150	200	150
t [mm]	4	3	4	4	5	4	5	4	4	5	5	4
f_y [MPa]	275											

2.2. Performance metrics

The FreeGrid methodological framework is here adopted for the holistic assessment of the overall performance of the proposed ReBG solutions. Design goals, each expressed by a quantitative metric normalized to the BG counterpart, are evaluated and discussed. Some metrics are slightly modified with respect to the FreeGrid definition, to account for the reuse of reclaimed elements.

Design Goals are firstly grouped in three performance categories to consider structural, buildability, and sustainability (subscripts *s*, *b*, and *su*) aspects. Then, a bulk performance metric P is calculated as linear combination of partial performance metrics – appointed as P_s, P_b, and P_{su} – defined for the three performance categories, as provided in Eq. (3).

$$P = \gamma_s P_s + \gamma_b P_b + \gamma_{su} P_{su} \tag{3}$$

with γ_s, γ_b, and γ_{su} the partial weighting factors that are equal to 1/3 to give the same weight to each partial metric P_s, P_b, and P_{su} are given by:

$$P_s = \frac{\sum_{k=1}^{2} \frac{\widehat{LF}_{k,ReBG}}{\widehat{LF}_{k,BG}} \Big/ \frac{|\hat{\delta}_{z,k,ReBG}|}{|\hat{\delta}_{z,k,BG}|}}{2}; \quad P_b = \frac{1}{\frac{1}{5}\left[\frac{1+\bar{\Delta}_{ReBG}}{1+\bar{\Delta}_{BG}} + \frac{\#(N_{ReBG})}{\#(N_{BG})} + \frac{\#(J_{ReBG})}{\#(J_{BG})} + \frac{1+\tilde{l}_{ReBG}}{1+\tilde{l}_{BG}} + \frac{\#(C_{ReBG})}{\#(C_{BG})}\right]}; \quad P_{su} = \frac{1}{\frac{W_{ReBG}}{W_{BG}}} \tag{4}$$

The P_s *structural performance metric* considers both stability ($\widehat{LF}_k$) and deformability ($|\hat{\delta}_{z,k}|$) issues for each load condition LC_1 and LC_2. In FreeGrid, fully nonlinear analyses are required for computing $\widehat{LF}_k$ as the minimum between the load multipliers corresponding to two possible failure modes: (i) global, local or member elastic-plastic instability; (ii) full plasticization of at least one cross section. Differently from FreeGrid, $\widehat{LF}_k$ here is a conventional load factor at ULS, which approximately accounts for interaction between plastic behaviour and elastic instability through the *Merchant-Rankine* formula [5, 6], as:

$$\widehat{LF}_k = \frac{1}{\frac{1}{\widehat{LF}_{P,k}} + \frac{1}{\widehat{LF}_{B,k}}} \tag{5}$$

where: $\widehat{LF}_{P,k}$ is the Load Factor for plasticity, and $\widehat{LF}_{B,k}$ is the Load Factor for elastic instability. Actually, $\widehat{LF}_{P,k}$ represents the load multiplier at the first yielding and is computed as the inverse of the maximum members' demand to capacity ratios, i.e. $\widehat{LF}_{P,k} = DCR_{MAX,k}^{-1}$, with Demand calculated by linear analyses and Capacity calculated according to the Eurocode 3 interaction formula for members under combined bending and axial compression [7]; $\widehat{LF}_{B,k}$ is the critical load multiplier at the first buckling mode, obtained by solving the linear eigenvalue problem for the perfect configuration under the assumption of small displacements.

The metric $|\hat{\delta}_{z,k}|$ is the modulus of the maximum vertical displacement at SLS and is used to assess the structural stiffness. Each solution shall satisfy: $\widehat{LF}_{P,k} \geq 1$, $\widehat{LF}_{B,k} \geq 1$, and $|\hat{\delta}_{z,k}| \leq \hat{\delta}_{z,lim} = B/200$, being $\hat{\delta}_{z,lim}$ the limit value of the maximum displacement.

The P_d *performance metric* considers several buildability issues, such as face-out-of-planarity ($\bar{\Delta}$), joint number (N), uniformity of structural joints (J) and members (C). The metric $\bar{\Delta}$ accounts for the face out-of-planarity in 2D gridshell panels and measures the average of the distances of the face vertices of each mesh from their projection on the best fitting plan, further divided by the face half perimeter. The metrics N, J, and C are the numbers of joints, types of joints, and structural members, while $\tilde{l}$ is the coefficient of variation of member lengths over the whole gridshell.

The P_{su} *performance metric* considers the environmental impact through the reduction of the metric W, given by:

$$W = \sum_{i=1}^{I} g_i \cdot l_i \cdot \alpha_i + \left(\sum_{r=1}^{R} g_r \cdot l_r \cdot \alpha_r\right) \cdot c_r \tag{6}$$

being W the gridshell embodied carbon associated with LCA module A1-A3; g_i, l_i, and α_i the weight per unit length, the length and the embodied carbon correction coefficient of the i-th new structural member; g_r, l_r, and $\alpha_r = \alpha_i$ the counterparts for the r-th reused structural member; i = 1, …, I, with I the total number of new structural members and r = 1, …, R with R the total number of reused structural members; c_r a correction factor. The coefficient α_i has been derived in [1-3] by fitting laws as a function of the section type, according to the formula $\alpha_i = 0.939 + 0.0002 \cdot f_y$ for hollow sections, with the steel grade f_y expressed in [MPa].

For reused sections the embodied carbon associated with LCA module A1-A3 is replaceable with the embodied carbon derived from selective deconstruction, considered as the production process of steel sections to be reused. For this aim, the correction factor c_r is introduced in Eq. (6) and is defined as the ratio between the carbon factor for selective deconstruction, ECF_D, and the carbon factor for LCA module A1-A3, ECF_{A1-A3}, i.e.:

$$c_r = ECF_D / ECF_{A1-A3} \tag{7}$$

For ECF_D, a value of 0.27 $kgCO_{2eq}/kg$ is assumed, as derived in [8] to account for selective deconstruction, by disassembly of structure without connections and hoisting structural members through a mobile crane, while for ECF_{A1-A3}, a value of 2.5 $kgCO_{2eq}/kg$ is assumed, representing the general carbon factor globally used for steel hollow section and plate [9]; hence, in Eq. (7) the reduction coefficient is equal to c_r = 0.108. Since the embodied carbon associated to steel scraps – produced by the fitting of stock elements in the structural grid – is a very small quantity (order of 10^{-3}), it is neglected in this study; for example, in [8] it is assumed equal to $0.8068 \cdot 10^{-3}$ $kgCO_{2eq}/kg$.

3. The optimization problem

The optimization problem aims at reusing as many stock elements as possible in the structural grid. It can be defined as stock constrained optimization problem [10-11], where the element lengths act as design constraint. The starting grid on the design domain (i.e. the vault surface) is obtained from a certain number of points initially generated on a horizontal plane π and then projected on the vault surface S. A geometric optimization process is performed by means of a genetic algorithm; basically, by modifying the points coordinates, the algorithm tries to find a grid where elements have lengths equal (within a stetted tolerance) to the lengths of the elements available in the stock. Hence, loads and constraints are applied to the structural grid and the mechanical aspect of the optimization problem is accounted as well. The result grid is a (local) optimal solution, characterized by a certain percentage of reused elements and satisfying all design constraints. This procedure, illustrated in Fig. 2, is carried out using different objective functions and constraints, as explained in following paragraph. The optimal ReBGs are shown in Fig. 3, in which the new and reused members are respectively depicted with blue and green lines; the percentage of new and reused members is also provided in the figure, which varies between 17% - 19% for $ReBG_q$ solutions and between 39% - 63% for $ReBG_d$.

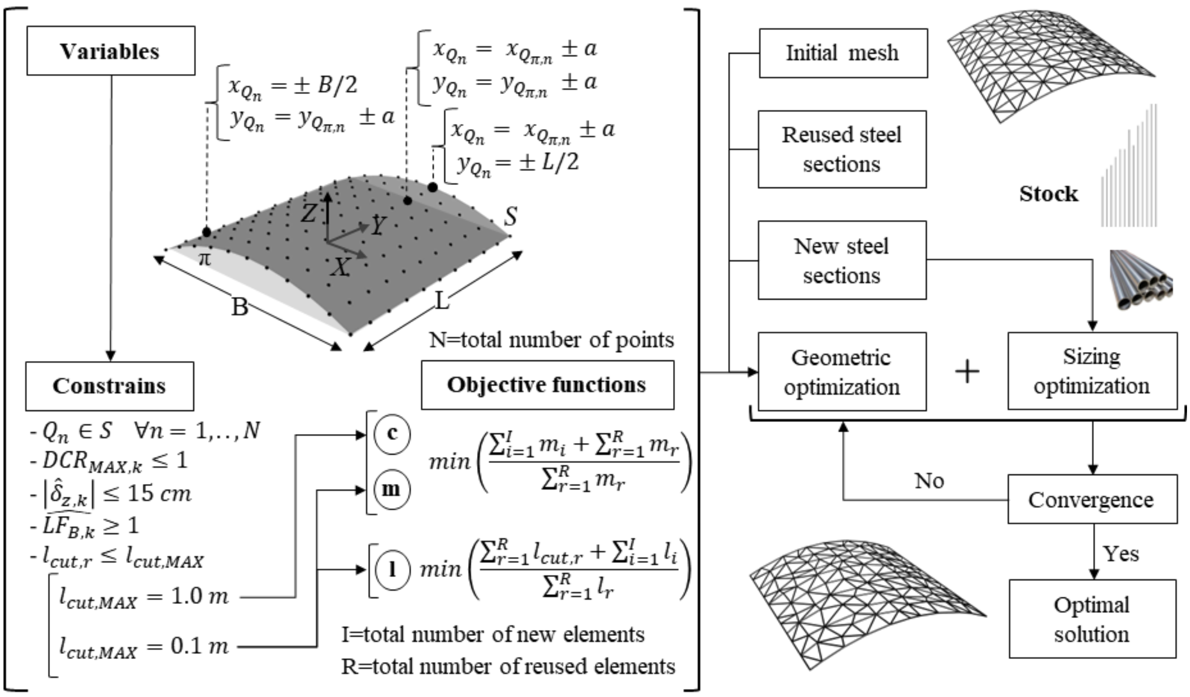

Figure 2: Optimization process layout

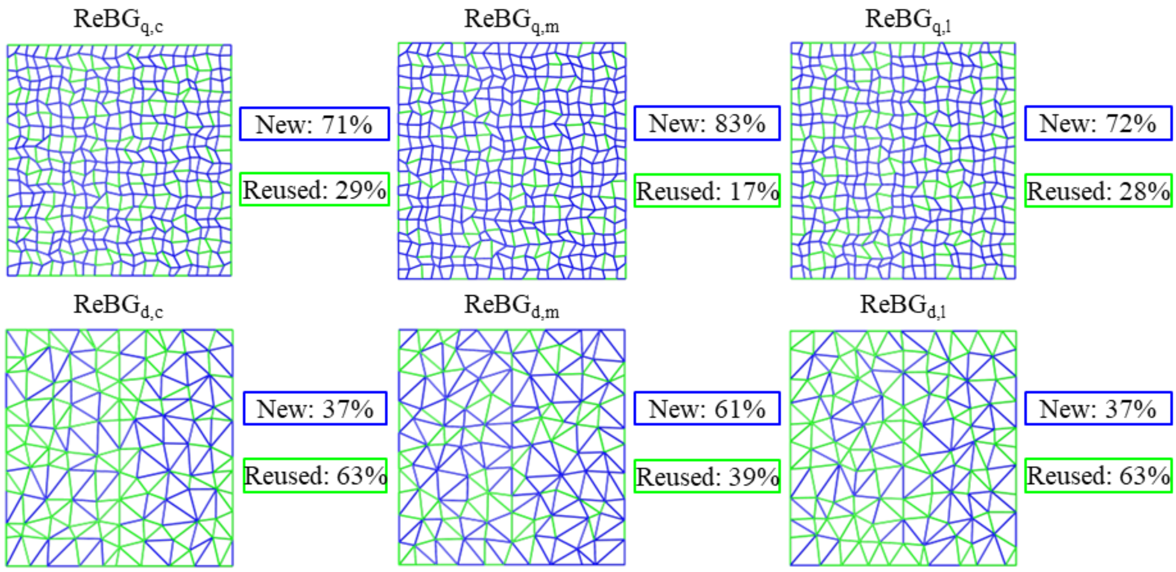

Figure 3: Optimal ReBG solutions

3.1. Objective functions

Two different objective functions, involving different parameters, are considered.

With the first one, the algorithm tries to maximize the number of reused elements and minimize the total structural mass, thus minimizing the whole fraction; in particular, $\sum_{i=1}^{I} m_i$ is the total mass of new elements (with i = 1, …, I) and $\sum_{r=1}^{R} m_r$ the total mass of reused elements (with r = 1, …, R). With this objective function two different types of optimization process are carried out: in the first one, appointed as "*c*", the algorithm associates the reused elements to a position between two points of the grid whenever the distance between the points is not larger than the element length, as provided in Fig. 2; in the second one, appointed as "*m*", in order to avoid section cutting, the algorithm associates the reused elements to the grid only if the element length perfectly fits the grid nodes distance with a tolerance of ± 10 cm. In the "*c*" optimization process, the possibility of element cutting is considered – as also done by other authors [11, 12] – and the maximum cutting length, $l_{cut,MAX}$, which can be specified based on the stock characteristics, is here assumed equal to 1.0 m; instead, in the "*m*" optimization process, $l_{cut,MAX}$ = 0.1 m.

With the second objective function, appointed as "*l*", the algorithm aims at maximizing the length of reused elements while minimizing the length of new elements and the cutting length; in particular, $\sum_{i=1}^{I} l_i$ is the total length of new elements, $\sum_{r=1}^{R} l_r$ is the total length of reused elements, and $\sum_{r=1}^{R} l_{cut,r}$ is the total cutting length of reused elements. A similar approach, aimed at minimizing the cutting length, has been proposed by Van Marcke et al. [12].

In all cases, the mechanical optimization process allows for assigning the structural section that best meets all structural constraints to the new elements.

3.2 Variables

The variables of the optimization problem are the point coordinates in the design domain. In fact, for a generic internal point Q_n, the x and y coordinates of its projection on the ground level plane π, can be increased or decreased randomly, and independently from all other points, through a coefficient factor a. In particular, $x_{Q\pi,n}$ and $y_{Q\pi,n}$ represent the coordinates in the plane π while x_{Qn} and y_{Qn} the corresponding counterparts on the gridshell surface S; for ReBG solutions with quadrangular units, the coefficient a = ± 0.5 m while for diagonalized units, a = ± 1.5 m.

Points along the two perimeter generatrixes and the spring lines respectively follow the same rule only for their x and y coordinate, due to the fact that the perimeter of the vault is fixed. Another variable is related to the cross section of the new elements that satisfies in optimal way all the structural constraints.

3.3 Constrains

The constraints of the problem are both geometric and structural. Firstly, each point should belong to the surface of the vault S, i.e. $Q_n \in S$, whose geometry should not change. For each element and for both conditions LC_k, the maximum DCR at ULS design, should be less than 1. Once identified the maximum utilization through the whole grid, $DCR_{MAX,k}^{-1}$ provides the load multiplier corresponding to the first yielding, i.e. $\widehat{LF}_{P,k}$. The maximum displacement at SLS design $|\hat{\delta}_{z,k}|$ must be less than the limit displacement $\hat{\delta}_{z,lim}$. In order to account for the global structural performance, the elastic critical load multiplier $\widehat{LF}_{B,k}$ is also calculated, and this value should be larger than 1. When the possibility of cutting reused element is considered, a maximum cutting length (here assumed equal to 1 m), i.e. $l_{cut,r} \leq l_{cut,MAX}$, is introduced to limit the total amount of steel scraps.

4. Results and performance assessment

The main results of the different BG and ReBG solutions are collected in Figs. 4 and 5, respectively for quadrangular and diagonalized units. For each load condition LC_k, the results are provided in terms of load factors $\widehat{LF}_B$ and $\widehat{LF}_P$, unit structural mass m/A_S (i.e. the ratio between the total mass of the structural steel utilized for each solution and the total floor area of the gridshell), and maximum displacement ratio $|\hat{\delta}_z|/\hat{\delta}_{z,lim}$. For the sake of conciseness, the subscript k indicating the *k*-th load condition is omitted in the figures.

From the figures it can be seen that BGs are characterized by almost the same mass, slightly smaller for the diagonalized units. ReBGs are lighter than BGs, with m/A_S of ReBG that is around 0.5 times the BG counterpart for quadrangular units and 0.3 times the corresponding BG for diagonalized units. The ratio $|\hat{\delta}_z|/\hat{\delta}_{z,lim}$ is always much smaller than 1 for LC_1 and smaller than 1 for LC_2; the diagonalized units are characterized by the smallest displacements, since the triangular grid is stiffer than the quadrangular counterpart. BG_q is characterized by values of load factors smaller than BG_d, except in the case of $\widehat{LF}_P$ for LC_1; BGs and $ReBG_q$ solutions are characterized by $\widehat{LF}_P$ smaller than $\widehat{LF}_P$ for LC_1 – except for $ReBG_{d,l}$ – and by $\widehat{LF}_P$ smaller than $\widehat{LF}_B$ for LC_2.

Goal and performance metrics introduced in section 2 are here calculated for BG and ReBG solutions; goal metrics are given in Tables 2 and 3 for BGs and ReBGs, respectively, while partial and bulk performance metrics are given in Table 4 for each solution.

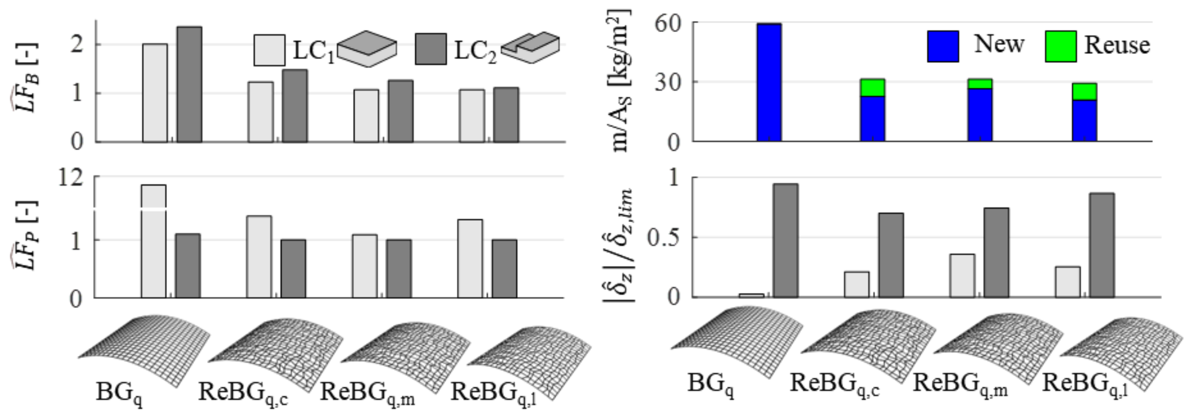

Figure 4: Main results of the BG and ReBG solutions with quadrangular units

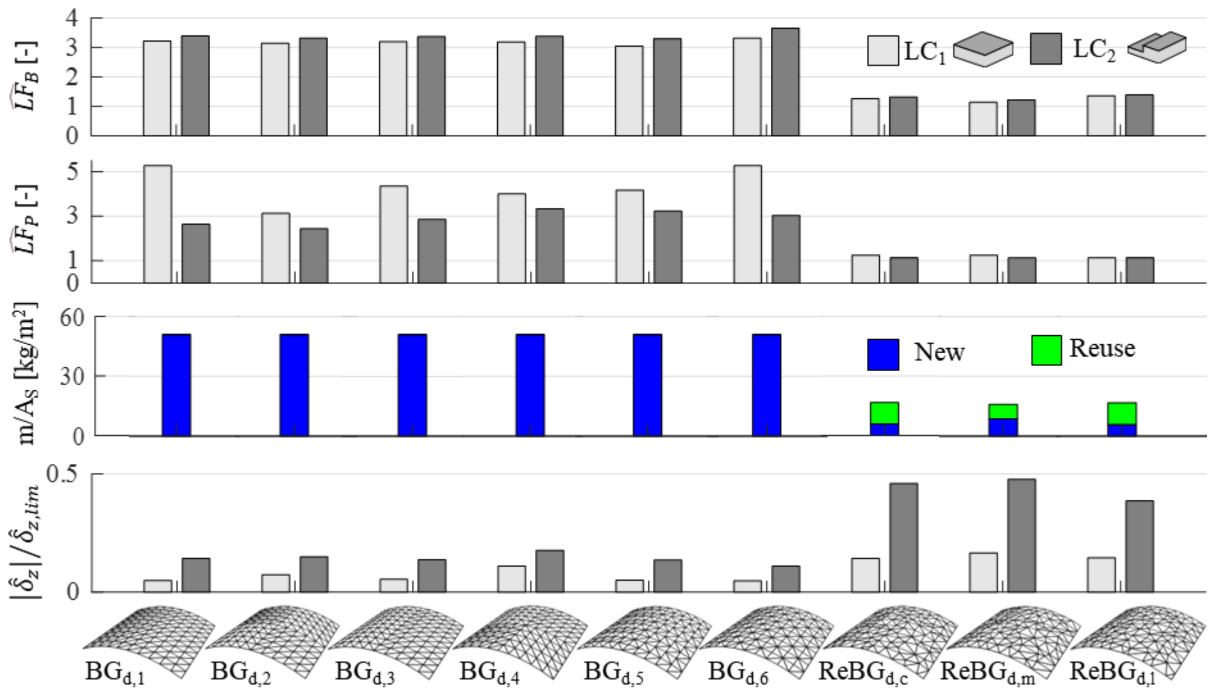

Figure 5: Main results of the BG and ReBG solutions with diagonalized units

Regarding the Structural Goal Metrics, similar comments to the ones traced in Figs. 4 and 5 can be drawn in terms of load factors and maximum displacements. Considering the Buildability Goal Metrics, ReBGs are characterized by values of *J* and *C* much larger than the BGs counterparts (i.e. larger non-uniformity of structural joints and members), and these values are even larger in ReBG$_q$ solutions, since the number of joints *N* is much larger than the counterpart in ReBG$_d$ solutions. With reference to the Sustainability Goal Metric, as expected, the ReBGs show values smaller than the BGs counterparts, with *W* of ReBG that is around 0.5 times the BG counterpart for quadrangular units and 0.3 times the corresponding BG for diagonalized units.

Table 2: Goal Metrics for BG solutions

solution	*SGM*						*BGM*					*SuGM*
	$\widehat{LF}_{B,1}$ [-]	$\widehat{LF}_{P,1}$ [-]	$\lvert\hat{\delta}_{z,1}\rvert$ [cm]	$\widehat{LF}_{B,2}$ [-]	$\widehat{LF}_{P,2}$ [-]	$\lvert\hat{\delta}_{z,2}\rvert$ [cm]	$\lvert 1+\bar{\Delta}\rvert$ [-]	#(*N*) [-]	#(*J*) [-]	$1+\tilde{l}$ [-]	#(*C*) [-]	*W* [kg]
BG$_q$	2.01	11.11	0.39	2.36	1.10	14.18	1	441	4	1	1	57556
BG$_{d1}$	3.22	5.26	0.73	3.39	2.63	2.15	1	121	5	1.17	1	49561
BG$_{d2}$	3.14	3.13	1.10	3.32	2.44	2.25	1	121	11	1.17	1	49561
BG$_{d3}$	3.20	4.35	0.81	3.37	2.86	2.06	1	121	10	1.17	1	49561
BG$_{d4}$	3.19	4.00	1.66	3.38	3.33	2.65	1	121	11	1.17	1	49561
BG$_{d5}$	3.05	4.17	0.76	3.30	3.23	2.04	1	121	9	1.17	1	49561
BG$_{d6}$	3.32	5.26	0.72	3.66	3.03	1.65	1	121	7	1.17	1	49561

KEY: *SGM* = Structural Goal Metrics, *BGM* = Buildability Goal Metrics, *SuGM* = Sustainability Goal Metric.

Table 3: Goal Metrics for ReBG solutions

solution	*SGM*						*BGM*					*SuGM*
	$\widehat{LF}_{B,1}$ [-]	$\widehat{LF}_{P,1}$ [-]	$\lvert\hat{\delta}_{z,1}\rvert$ [cm]	$\widehat{LF}_{B,2}$ [-]	$\widehat{LF}_{P,2}$ [-]	$\lvert\hat{\delta}_{z,2}\rvert$ [cm]	$\lvert 1+\bar{\Delta}\rvert$ [-]	#(*N*) [-]	#(*J*) [-]	$1+\tilde{l}$ [-]	#(*C*) [-]	*W* [kg]
ReBG$_{q,c}$	1.23	1.41	3.18	1.48	1.00	10.53	1.001	441	392	1.242	38	23358
ReBG$_{q,m}$	1.07	1.09	5.37	1.26	1.00	11.16	1.001	441	401	1.238	32	26799
ReBG$_{q,l}$	1.07	1.35	3.79	1.11	1.00	12.99	1.001	441	397	1.245	31	21568
ReBG$_{d,c}$	1.26	1.25	2.14	1.31	1.14	6.9	1	121	119	1.234	20	6902
ReBG$_{dm}$	1.14	1.25	2.49	1.22	1.12	7.17	1	121	119	1.236	20	9336
ReBG$_{d,l}$	1.36	1.14	2.19	1.39	1.14	5.8	1	121	117	1.223	19	6886

KEY: *SGM* = Structural Goal Metrics, *BGM* = Buildability Goal Metrics, *SuGM* = Sustainability Goal Metric.

Looking at partial and bulk performance metrics for each ReBG solution, from Table 4 it can be observed that P_s and P_b are smaller than 1 with P_b assuming values much smaller than P_s, particularly for solutions with quadrangular units due to the high values of #(N) and #(J) (Table 3). Considering the diagonalized units, instead, P_s and P_b have almost the same value. P_{su} is always much larger than 1 thanks to the adoption of reused steel members; therefore, P is almost equal to 1 for solutions with quadrangular units and much larger than 1 (up to 2.5) for solutions with diagonalized units.

Table 4: Partial and Bulk performance metrics

solutions		P_s [-]	P_b [-]	P_{su} [-]	P [-]
$ReBG_{q,c}$	BG_q	0.56	0.04	2.46	1.02
$ReBG_{q,m}$	BG_q	0.48	0.04	2.15	0.89
$ReBG_{q,l}$	BG_q	0.40	0.04	2.67	1.04
$ReBG_{d,c}$	$BG_{d,1}$	0.12	0.11	7.18	2.47
	$BG_{d,2}$	0.17	0.15	7.18	2.50
	$BG_{d,3}$	0.12	0.14	7.18	2.48
	$BG_{d,4}$	0.21	0.15	7.18	2.51
	$BG_{d,5}$	0.12	0.14	7.18	2.48
	$BG_{d,6}$	0.10	0.12	7.18	2.47
$ReBG_{d,m}$	$BG_{d,1}$	0.10	0.11	5.31	1.84
	$BG_{d,2}$	0.15	0.15	5.31	1.87
	$BG_{d,3}$	0.11	0.14	5.31	1.85
	$BG_{d,4}$	0.18	0.15	5.31	1.88
	$BG_{d,5}$	0.10	0.14	5.31	1.85
	$BG_{d,6}$	0.08	0.12	5.31	1.84
$ReBG_{d,l}$	$BG_{d,1}$	0.13	0.11	7.20	2.48
	$BG_{d,2}$	0.19	0.15	7.20	2.51
	$BG_{d,3}$	0.13	0.15	7.20	2.49
	$BG_{d,4}$	0.22	0.15	7.20	2.52
	$BG_{d,5}$	0.13	0.14	7.20	2.49
	$BG_{d,6}$	0.10	0.13	7.20	2.48

5. Conclusions

This paper presents a preliminary exploration of gridshell design based on the reuse of reclaimed steel members. A barrel vault has been selected within the FreeGrid benchmark context (the background, fully constrained, barrel vault) and utilised as case study; a stock of steel elements has been generated and adopted as virtual inventory of structural members. An optimization procedure focusing at maximizing the reused elements has been proposed and some grid solutions have been obtained. In this initial phase of the research, linear analyses have been carried out for the optimization and the structural assessment of the design solutions; this assumption, as well as the consideration of reused elements, have required some modifications to the performance metrics and the method for performance assessment. As stated in the introduction, this study has strived to achieve a good level of overall performance (accounting for structural response, buildability and sustainability) by mainly focusing on the sustainability aspects. In fact, almost all the reuse-based design solutions are characterised by values of the bulk performance metrics larger than one, with only two exceptions. However, some refinement in the optimization process should be introduced, to better consider the mechanical aspects together with the geometrical ones and to achieve structural safety levels for the design solutions not lower than the Background counterparts. Further, the results here obtained should be confirmed by fully nonlinear analyses, as normally done for gridshell design. Finally, sensitivity analyses should be carried out by varying the element stock, considering both different generation criteria for the virtual stocks and real inventories, made of components salvaged from real constructions.

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