Novel Morphologies of Aluminium Cross-Sections through Structural Topology Optimization Techniques

Lukas GREKAVICIUS[1,a], Jack Antony HUGHES[1,b], Konstantinos Daniel TSAVDARIDIS[1,c] and Evangelos EFTHYMIOU[2,d *]

[1] Institute for Resilient Infrastructure, School of Civil Engineering, University of Leeds, Woodhouse Lane, LS2 9JT, Leeds, UK

[2] Institute of Metal Structures, Department of Civil Engineering, Aristotle University of Thessaloniki, GR 54124, Thessaloniki, Greece

[a]cn11l2g@leeds.ac.uk, [b]cn12jah@leeds.ac.uk, [c]k.tsavdaridis@leeds.ac.uk, [d,*]vefth@civil.auth.gr

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Abstract. In the last decades, the deployment of aluminium and its alloys in civil engineering fields has been increased significantly, due to the material's special features accompanied by supportive technological and industrial development. However, the extent of aluminium structural applications in building activities is still rather limited and barriers related to strength and stability issues prevent its wider use. In the context of the extrusion characteristic, appropriate design in aluminium cross-sections can overcome inherent deficiencies, such as the material's low elastic modulus.

This paper investigates a new breed of cross-sectional design for aluminium members employing pioneering structural topology optimisation techniques. Topology optimisation problems utilise the firmest mathematical basis, to account for improved weight-to-stiffness ratio and perceived aesthetic appeal of specific structural forms. The current study investigates the application of structural topology optimisation to the design of aluminium beam and column cross-sections. Through a combination of 2D and 3D approaches, with a focus on post-processing and manufacturability, ten unique cross-sectional profiles are proposed. Additionally, the variation of cross-section along the member is also investigated in order to identify correlation between 2D and 3D topology optimisation results. Conclusions attempt to highlight the advantageous characteristics of aluminium use as well as the potential benefits to the more widespread implementation of topology optimization within the utilization of aluminium in civil/structural engineering.

Introduction

Aluminium is a unique material that has the potential of competing within the construction industry. Successful application of aluminium alloys in structural engineering is connected to its inherent physical and mechanical properties: low density, which allows reduced loads on foundations and easier construction process; excellent corrosion resistance, which reduces its maintenance requirements; and the extrusion process, which allows the production of members with efficient and optimised cross-sections [1]. In particular, although available for some other non-ferrous metals, such as brass and bronze, it is with aluminium that the extrusion process has become a major manufacturing method [2]. The extrusion process allows aluminium sections to be formed in an almost unlimited range of shapes, while a significant advantage is the ability to produce sections that are very thin relative to their overall size [3].

Aluminium cross-sections are separated into four classes based on b/t ratio limits of reinforced and un-reinforced parts. When compared to standardised steel sections, aluminium cross-sections are often asymmetric, more complex, contain thin walls and are reinforced with ribs, bulbs and lips [4]. Local instability is therefore the governing factor when designing such sections. Another factor that is linearly related to buckling resistance of beams and columns is the stiffness of cross-sections (EI).

To compensate for the low elastic modulus and achieve higher stiffness, the moment of inertia has to be increased. When considering standard shapes this would result in deeper and more slender sections, which are more susceptible to buckling. However, sections obtained through topology optimisation can achieve a high I-value with an optimal amount of material.

Structural topology optimisation is based on the principle of optimising the number and size of openings within a design space, in order to satisfy the applied loading and constraints. There are numerous topology optimisation techniques available in the market. The currently most popular one is the Solid Isotropic Material Penalisation (SIMP) technique, which is based on discretising the design domain into finite elements and utilising FE analysis to vary the densities in each element. Depending on the intensity of stresses, the elements are characterised as being low, high or intermediate density [5]. The process is iterative until convergence is reached. Topologies often resemble complex natural forms; therefore, it is often up to the designer to interpret them. Interpretation is a crucial part of the overall optimisation process and needs to be performed carefully with consideration of manufacturing and practicality factors. This has been unaddressed in existing literature. Previous research has however attempted to optimise both the length and cross-section of beams and columns. 2D approaches, such as that taken by Anand and Misra [6], are effective for identifying a range of potential cross-sectional shapes with a wide variety of load and support conditions. Bochenek and Tajs-Zielińska [7] have demonstrated that through a 3D approach, variations in bending and shear along the length of a column result in a non-uniform cross-section. Zuberi, Zhengxing and Kai [8] attempted to overcome this issue through the use of an extrusion constraint, however the resulting cross-sections are limited to overly simplistic shapes that are likely susceptible to local buckling phenomena due to the slender webs.

The previous work is limited to a select few simple load conditions and there have not been any attempts made at optimising aluminium cross-sections. Therefore, this study aims to utilise its potential and propose new efficient structural shapes by conducting cross-sectional topology optimisation analysis of 6063-T6 aluminium alloy beams and columns. It is intended to achieve a minimum possible weight with maximum stiffness, as weight savings can render significant reductions in manufacturing and construction costs, as well as environmental impact.

Topology Optimisation Approach

This research undertook a combination of approaches, in order to consider all necessary degrees of freedom identified in Fig. 1. A 2D approach was used to identify a wide variety of cross-sectional profiles, however this approach did not consider variations in bending and shear along the length of the member. A 3D approach was then used to provide a series of comparative cross-sectional slices, to capture the effect of this variation. All optimisation was performed using Altair Engineering's software package HyperWorks v13.0. Through this, more than 40 different combinations of loading and support conditions were analysed. Loading conditions were chosen with reference to the standard cross-section classification procedure for outstand and internal compression elements given by codified provisions [9].

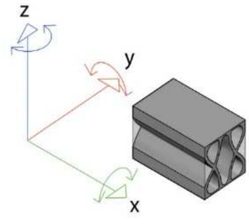


Figure 1. Considered directions of rotation and translation

Linear static analysis was performed on an elastic material model with the following properties: Young's modulus of 70 GPa, Poisson's ratio of 0.3, shear modulus of 27 GPa and density of 2700 kg/m^3. Shell elements with a nominal size of 1 mm and solid elements with a nominal size of 5 mm were used to model the 2D and 3D members, respectively.

A simple load case of a uniform load to the top edge was considered initially (Fig. 2 a). After numerous trials, all models have been optimised for minimum compliance (therefore maximum stiffness) subject to a constraint on the final volume fraction of 0.275 (Fig. 2 b). Manufacturability was addressed by adding symmetry constraints, which subsequently improved the clarity of the results (Fig. 2 c). In order to then prevent checker-boarding (patterns of alternating solid and void elements) within the results, minimum member size limit has been set to 7 mm (Fig. 2 d). Results are presented as contour plots of the element densities and it can be observed that a high concentration of material is distributed close to supports. The topology then follows lines of principal stresses.

This optimisation problem has been validated in both the 2D and 3D cases. When compared to the results obtained by Anand and Misra [6] and Zuberi, Zhengxing and Kai [8] a close agreement of the patterns has been identified.

Identical analysis has been performed to compare topologies obtained with aluminium and steel. Aluminium alloy 6063-T6 (with a tensile strength of 245 N/mm^2) was compared to grade S355 steel with Young's modulus of 210 GPa and Poisson's ratio of 0.3. The result for steel is shown in Fig. 2 e), for comparison against Fig. 2 d). Identical topologies reveal that the optimisation constraints and geometry are dominant, therefore the results are applicable to both materials.

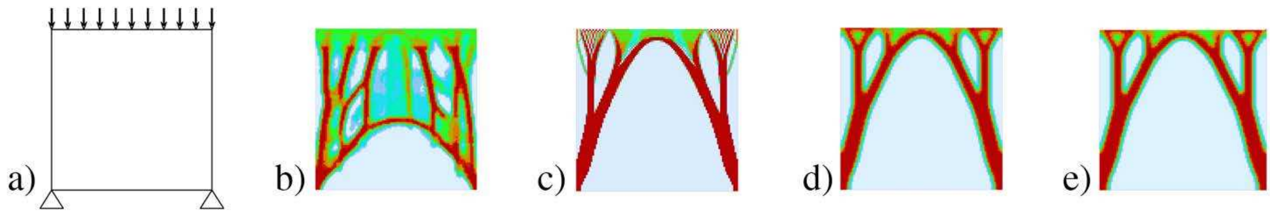


Figure 2. Development of the initial model topologies (a, b, c, d) and topology of S355 Steel (e)

A 100x100mm square section has been chosen as the initial design domain in order to provide maximum flexibility in the resulting topologies. So as to provide a comparison however, sections with aspect ratios of 100x200mm and 200x100mm have also been optimised. Fig. 3 demonstrates that very similar density plots are achieved regardless of the aspect ratio, therefore the sections may be adapted into similar forms as required.

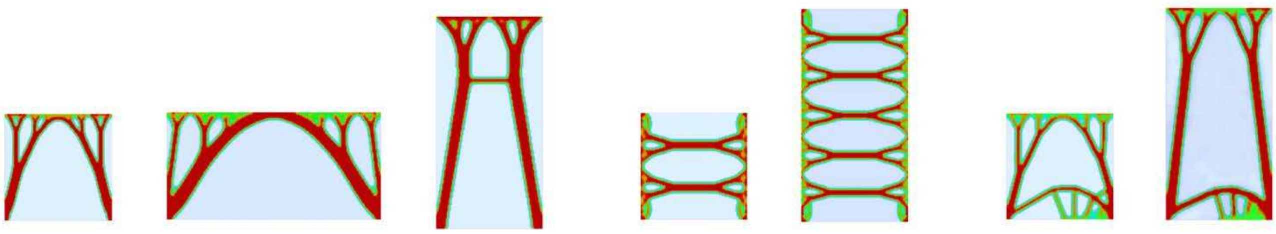


Figure 3. Topologies of cross-sections with various aspect ratios

As discussed in the previous chapter, topology optimisation results must be carefully interpreted into a suitable structure. The results are highly sensitive to geometry, so a method of post-processing multiple results to allow for these sensitivities is proposed. The contour plots shown previously have been smoothed with a density threshold of 0.3 using Altair Engineering's OSSmooth and extracted into AutoCAD. Afterwards, the results from multiple loading and support conditions have been overlaid and presented in a form appearing similar to x-rays. These show the most frequently stressed material to be darker in colour and allow for the interaction of various load cases to be considered.

Optimisation processes for lightweight structures typically result in thin-walled cross-sections. When combined with aluminium's lower modulus of elasticity, local instability modes including distortional and local buckling are typically dominant. In order to minimise the likelihood of these failures, optimal placement of compression members and stiffeners is of vital importance. Using the described post-processing method, this stability criterion should be satisfied by comparing the typical stresses in cross-sections subjected to torsion, compression, yielding and one or two plane buckling.

Topology Optimisation of Cross-sections

Beams. Pinned supports to 2 and 4 nodes are compared, in order to propose sections suitable for simply supported and fixed beams respectively. Major axis bending and torsion have then been applied. Fig. 4 shows 5 beam cross-sections developed after processing. Above are the x-ray images with the original topologies, and below is the final interpreted section and its centroid. Section properties are then presented in Table 1. For beams that are primarily subjected to bending about one axis only, the proposed sections are symmetric about one plane. Asymmetric cross-sections are also included for additional stiffness when subjected to torsion. Regardless of the applied symmetry, it is noticed that the topology results have a similar moment of inertia about both axes.

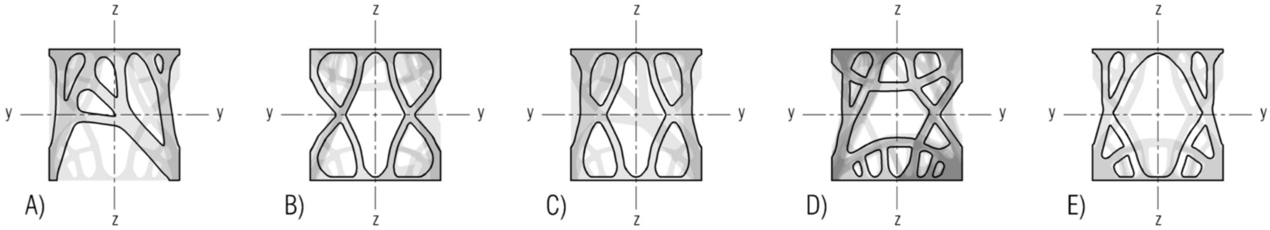
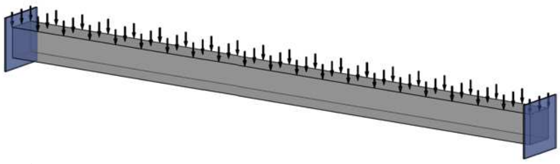


Figure 4. Post-processing of beam cross-sections. Overlaid results (top) and final interpretations (bottom)

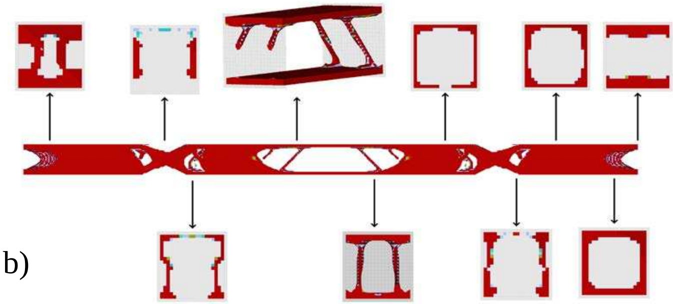
Table 1. Beam section properties

Section	A	B	C	D	E
Area [cm^2]	44.39	30.32	39.43	48.84	37.82
Moment of inertia, y [cm^4]	340.26	337.32	399.50	528.69	436.66
Moment of inertia, z [cm^4]	448.14	312.46	423.15	479.10	426.65
Radius of gyration, y [cm]	2.77	3.34	3.18	3.29	3.40
Radius of gyration, z [cm]	3.18	3.21	3.28	3.13	3.36

3D optimisation was performed on a 2 m extruded 100mm square beam, with total of six different loading and support combinations; including the case of fixed supports and a uniformly distributed load to the top flange as shown in Fig. 5 a. These reveal constant cross-sections such as elliptical hollow profile across 45-50% of the length of the beam. The remaining portion shows three distinct regions of low stress at approximately ¼, ½, and ¾ of the span, as seen in Fig. 5. These regions are observed to correspond with the intersections of the lines of principal tensile and compressive stresses in a homogeneous beam.



a)



b)

Figure 5. 3D optimisation input (a) and resulting topology with cross-sectional slices (b)

Columns. Optimisation of 2D column cross-sections with various support and loading conditions was initially attempted. Sections with two and four corner pin supports were analysed, subjected to axial compression, which include failure by yielding and one or two plane buckling. Column cross-sections found in practice are most commonly symmetric and have high buckling resistance about one or more axes depending on specific applications, hence the logic followed in developing the final cross-sections is shown in Fig. 6.

The first attempt considers a column under pure compression, such cross-sectional profile would reach its yield stress limit and experience material failure. The shape resembles a standard double webbed compound column cross-section used in the industry. The second attempt considers column failure due to buckling. Fig. 6 B and C represent a cross-sectional profile of a column having high stiffness in the y-y axis. The cross-sections are a combination of resulting stress plots with loading replicating compression and bending of a member as it buckles. Therefore, they are applicable in cases when an eccentric axial load or a moment are applied triggering one plane buckling. Sections presented in Fig. 6 D and E are resistant to compression and buckling in two axes. These profiles have equal stiffness in both axes and appear more resistant to local buckling. The section properties are presented in Table 2.

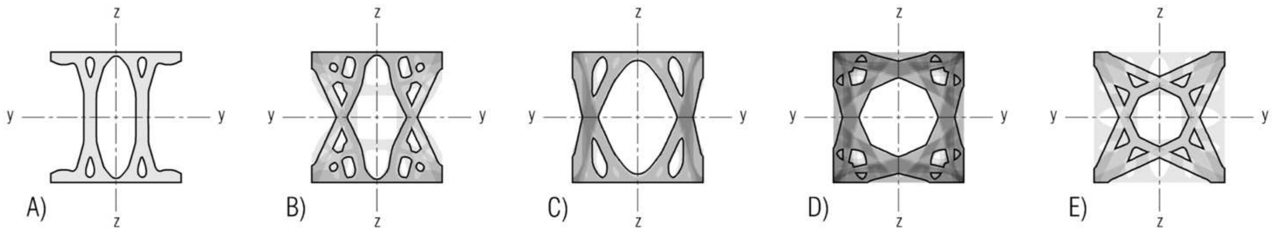


Figure 6. Post-processing of column cross-sections. Overlaid results (top) and final interpretations (bottom)

Table 2. Column section properties

Section	A	B	C	D	E
Area [cm^2]	35.36	49.95	52.00	59.13	49.10
Moment of inertia, y [cm^4]	461.63	565.23	582.67	608.38	442.67
Moment of inertia, z [cm^4]	224.58	449.33	578.80	608.38	442.67
Radius of gyration, y [cm]	3.61	3.36	3.35	3.21	3.00
Radius of gyration, z [cm]	2.52	3.00	3.34	3.21	3.00

3D optimisation was performed on a 2 m extruded 100x100 mm square column with fixed-pinned supports as shown in Fig. 7 a. An axial compressive load was applied at the top and loads triggering buckling in two planes – in the middle of the member. Symmetry manufacturing constraint was applied to the model about y-y and z-z axes. When subjected to two plane buckling the column developed concentrations of material at the four corners (Fig. 7), resembling a box section at multiple locations along the length of the member. Formation of a web connecting the flanges is also observed in the middle of the member at the location of the lateral load. The box shape of the cross-section could be related to the fully symmetric profiles obtained through 2D optimisation (Fig. 6 D and E).

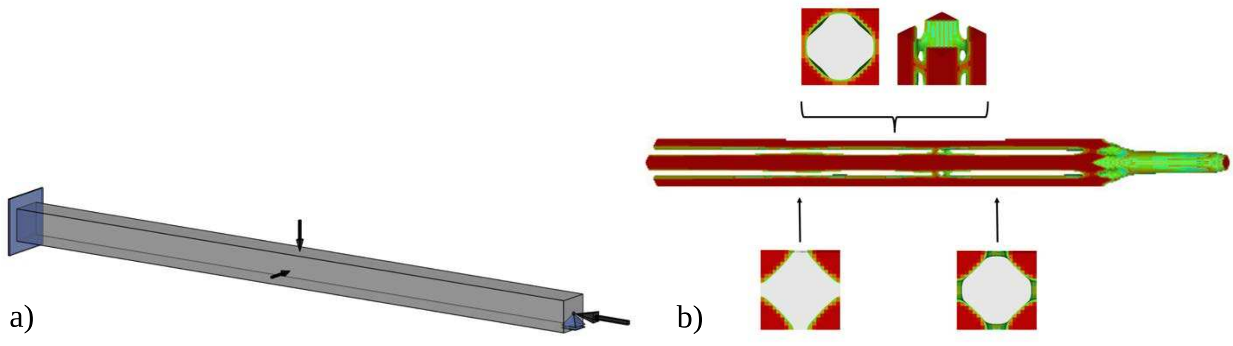


Figure 7. 3D optimisation input (a) and resulting topology with cross-sectional slices (b)

Concluding Remarks

In this paper, cross-sectional topology optimisation of aluminium structural members has been investigated. A series of unique topologies for a square 100x100 mm cross section have been generated using the SIMP technique, subject to different loading and support conditions. A tailored method for post-processing the 2D results is presented which aims to address stability and manufacturability criteria. Different density plots have been overlaid to identify the most frequently stressed areas of the cross-section, which resulted in 5 novel section profiles for beams and columns. A 3D optimisation approach was also presented to identify correlation between 2D and 3D results.

Both approaches for beams and columns predominantly result in complex hollow sections with various opening shapes, including square profiles with a central circular or elliptical opening. Due to the square design domain, most sections have a similar moment of inertia about both axes. Beam sections have an approximately central neutral axis despite only one plane of symmetry being applied. All column sections are symmetric about both axes and have high or equal stiffness about one or two axes, respectively. The 3D optimisation revealed some indicative regions where the novel cross-sections would be applicable. Nonetheless, the performance of the developed sections has to be tested in order to validate their applicability and competitiveness within the construction industry.

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