Tubular Structure Design Using Laser Cutting Technology

Square Hollow Sections

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Abstract

The present dissertation comes as an extension of the European research project LASTEICON which aimed at the simplification of steel connections using laser cutting technology. The primary objective was the improvement of the mechanical behaviour of the joints with a simpler detailing and less steel quantity while providing more quality, precision, and an environmentally friendly solution. This dissertation focuses on the use of steel tubular made trusses, with CHS and SHS cross-sections, where the connections were designed by creating an opening in the chords, using LCT, and extending its braces.

Considering the previously done experimental tests, performed in the IST laboratory, the approach adopted consisted of calibrating three numerical models, attesting for the accuracy of these models in representing the real structural behaviour of the trusses.

To establish a range of applicability and verify the benefits of using laser cut technology for this type of detail, in addition to a parametric analysis made for one of the trusses calibrated, a case study of the performance of these joints in a numerical model of a bigger structure was conducted. The results showed a substantial improvement in the global behaviour of the structure when compared to conventional manufacturing techniques, both in terms of resistance and stiffness.

Keywords:

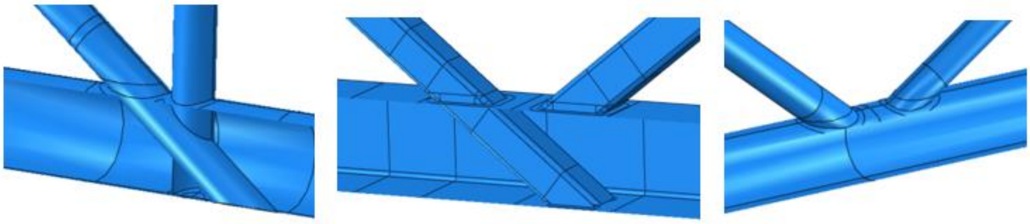
- Laser cutting technology
- Tubular steel structures
- Steel hollow section joints
- Welded joints
- Finite elements analysis

1. Introduction

According to the World Steel Association, after China, the EU is the second-largest producer of steel in the world, accounting for 8.5% of the global production [1]. With the production of 157 million tonnes of steel a year [1], the steel industry has a significant impact on the EU economy by endorsing employment and on the environment for increasing innovation and growth. Nonetheless, environmental and climate change regulation is a challenge for the industry. Notably, the most recent action plan, the European Green Deal, presented in December 2019, set a target of zero net emissions of greenhouse gases by 2050 [2].

Following the need to make the EU's economy sustainable and competitive, the Commission mobilized the Research Fund for Coal and Steel (RFCS), which financially supports research and innovation projects in the areas of coal and steel, in search of progressive technology and advanced production processes [3].

Intending to help achieve the targets set, the LASTEICON project was approved and funded. Using laser cut technology (LCT), its goal is to design new joint configurations that improve mechanical behaviour both for frame and truss structures, with less quantity of steel and simple detailing, proving to be an excellent alternative to the traditional type of connections. Additionally, these characteristics allow a more environmentally friendly solution with higher quality and precision, actively encouraging the use of hollow cross-sections. The use of LCT also reduces the risk associated with the fabrication process due to its computer-programmed automation [4]. Examples of the connections mentioned above are illustrated in Figure 1 for truss structures, where D2 extends half section of the two braces into the chord, D1 extends one brace into the chord and R is a traditional joint detail with both braces welded to the chord.



(a) (b) (c)

Figure 1: Examples of joint details: (a) CHS with D2 joint; (b) SHS with D1 joint; (c) CHS with R joint.

Following the research done in the scope of the LASTEICON project, that allowed exploiting the benefits of using laser cut technology, the work carried out in this dissertation aims to use ABAQUS, an advanced non-linear structural analysis software, not only to calibrate the numerical models but also do a parametric analysis to establish a range of applicability for this type of details and, ultimately, analyse the performance of laser-cut details in a larger scale truss.

2. Parametric studies

To validate the parametric study carried out within the scope of this dissertation, a calibration of the numerical modelling was in order. This refinement was done by comparing it with the experimental tests carried out prior in the IST laboratory, LERM [5]. Although other models were studied by previous IST researchers [6, 7, 8], this dissertation will focus on an SHS Warren truss with a D1 joint detail and S355 JR material, displayed in Figure 2. The S355 steel was numerically modelled according to the tensile tests previously performed [9], and thus, the mechanical characteristics applied to the FEM model are displayed in Table 1.

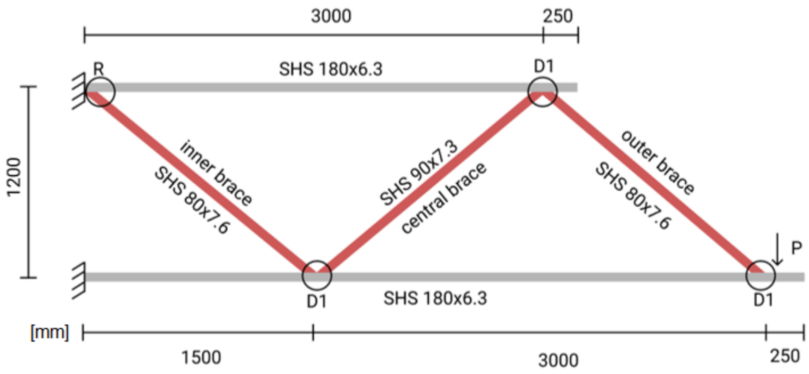


Figure 2: Model studied W_S_D1.

Table 1: Material properties of the FEM model for ABAQUS.

	S355
$f_y\ [MPa]$	366
$f_u\ [MPa]$	519
$\mathbf{E}\ [\mathbf{GPa}]$	210
$\rho\ [ton/mm^2]$	7.85E-9
ν	0.3

ABAQUS CAE was the software used to create the numerical model, with the chosen set of units [N, mm]. The truss was modelled with shell elements, decreasing stability problems during the analysis as well as achieving faster postprocessing. It was then opted to use S4R elements and refine the mesh in the areas with higher stresses gradients, namely in the joints. This way, a good ratio between computational time and solution precision is obtained.

A bilinear constitutive law was used to represent the non-linearity of the material in ABAQUS, with 0.01E for the strain-hardening, as suggested by Eurocode 3 [10]. Accounting for the non-linearity of the material, the type of analysis procedure used was Riks, which captures geometric nonlinearity, prior to buckling, as well as unstable post-buckling responses [11]. As shown in Figure 3, a fixed support was used to model the connection between the truss and the support structure at 250 mm from the extremity. Following the testing method implemented for the experimental tests, an imposed displacement of 400 mm was introduced in the numerical model in a reference point, connected to the corresponding cross-section, with a kinematic coupling constraint. In order to guarantee the type of joint affects the strength and stiffness of the truss, the design assured the failure mechanism is located at the most stressed joint, as represented in Figure 3. The truss was designed so that the failure would occur when the deformation on the most stressed node reached 3% of the diameter of the chord [12, 13].

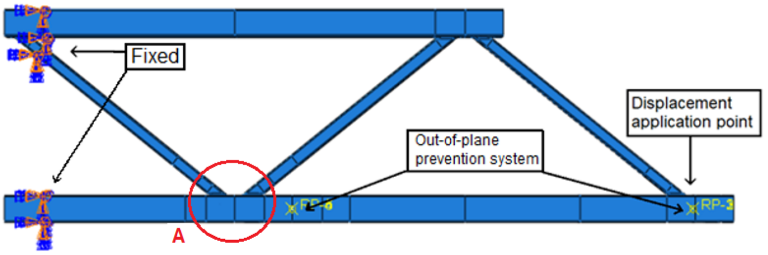
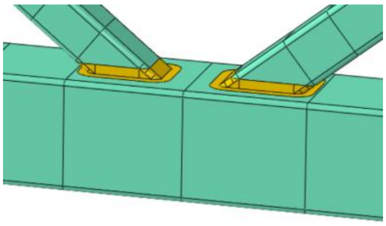


Figure 3: Displacement application point, lateral constrains and critical joint A.

To simulate the out-of-plan prevention system created in the experimental tests, springs were added to the numerical model, in the reference points present in Figure 3. The springs with non-linear stiffness distribution allowed the simulation of the gap, 5 mm for this model, between de truss and the prevention system, measured during the experimental study. There was no need to apply initial out-of-plane displacements in this particular model. It should be noted that a Pratt truss with a D2 detail and a Warren truss with a D1 joint detail but with a slope were also calibrated. The average value of the initial out-of-plane displacements applied to these three calibrated models was used for the parametric analysis.

The welding between the braces and the chords, exemplified in Figure 4, was simulated by partitioning the section around the connection of the elements and increasing its stiffness.



Welds	
f_y $[MPa]$	700
f_u $[MPa]$	900
E [GPa]	300
Width [mm]	15

Figure 4: Weld model on a Warren joint and weld’s characteristics.

After the calibration of the numerical model, a parametric study was carried out. To choose the parameters to be analysed, the equation, present in Eurocode 3 [9], to design the axial resistance of welded joints between SHS, was considered. Thus, the parameters considered are the type of detail in the critical joint (R, D1 or D2), the thickness and width of the chord in compression, the width of the brace in compression and tension, the yield strength of the chord and the eccentricity between the brace's axis. In total, 48 numerical models were studied by alternating the variation of each of the parameters. A D2 joint detail was employed in three models, with an 80 mm gap, to ascertain the influence of the increased joint rigidity in the truss, along with attaining a comparison of the performance between the three joint details covered in the context of this thesis. The dimensions of the profiles were obtained directly from the Celsius catalogue [14] and Figure 5 shows the generic truss used to model the cases studied.

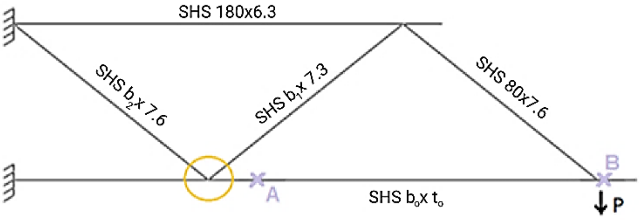


Figure 5: General Warren truss studied for the parametric analysis.

An initial horizontal out-of-plane displacement was applied to nodes A and B and a vertical one in node B, with a value of 167 mm, to consider possible initial rotations or displacements. Regarding the parametric study for the yield strength of the chord, the steel characteristics used can be viewed in Table 2.

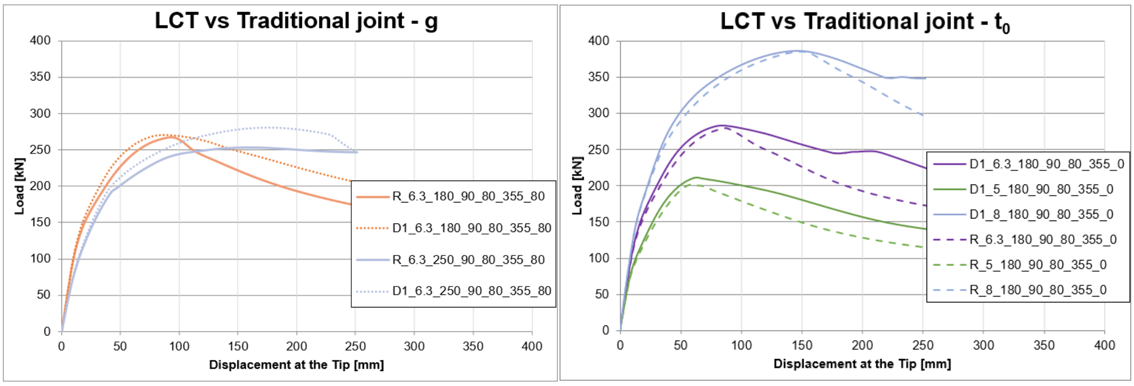
Table 2: Steel properties for ABAQUS.

	S355	S235	S275	S420	S460
f_y $[MPa]$	355	235	275	420	460
f_u $[MPa]$	510	360	430	540	560
ε	0.07381	0.05952	0.07381	0.05714	0.04762
E [GPa]			210		
ρ $[ton/mm^2]$			7.85E-9		
ν			0.3		

Analysing the results of the parametric study it was concluded that, instead of the failure mode occurring in the critical node, the truss is likely to buckle in the compressed brace for a chord thickness of 8 mm and a brace to chord slenderness ratio of 0.5, or superior.

When increasing the gap between the braces, for a D1 joint detail, large deformations of the bottom chord were observed. Therefore, a D2 detail was studied leading to different failure modes. For a thickness of the chord of 6.3 mm, the deformation occurred in the inferior chord and, for 8 mm, took place in the brace in compression. This can be explained by a significant increase of rigidity in the node, which caused the deformation to occur outside the connection.

Overall, comparing between a truss with a D1 and an R joint detail, it can be concluded that detail D1 has a better behaviour after buckling, not presenting such an accentuated slope, as well as a higher node resistance. However, in some cases, the difference between the peak loads is not very substantial. For a chord thickness of 6.3 mm, an increase of its width to 250 mm, was studied to inquire if it will increase the difference between joint details. As can be observed in Figure 6 (a), the joint D1 has more impact on the truss resistance for chords with more width.



(a) (b)

Figure 6: Load-displacement curve: (a) reflecting the chord's width influence; (b) comparison between D1 and R for the t_0 parameter study.

When observing Figure 6 (b), which compares the load-displacement curves of traditional and innovative LCT joints, it is perceptible that the influence of the type of detail depends on the thickness, and hence on the slenderness, of the truss elements. A truss with a 5 mm chord thickness has 4.14 % more influence in the truss resistance than one with a thickness of 8 mm.

To have a better perception of the way the detail applied to the critical node influences its deformation and resistance, Figure 7 was elaborated. Depicting a comparison between a D1, a D2 and an R joint detail, it is clear the major improvement in resistance capacity and rigidity that the D2 detail gives to the truss. Prolonging the two braces into the chord also led to the increase in the node rigidity and thus to a different failure mode, establishing the influence of the type of detail in the behaviour of the truss.

The influence of the innovative connections is also perceptible, for example, in Figure 8 (a), where a detail D1 leads to a change in the failure mode. The increase in the node rigidity leads to the deformation of the chord outside the connection. Figures 8 (b) establish that prolonging brace members impacts the failure mode of the truss, inducing buckling on the compressed brace instead of the critical node.

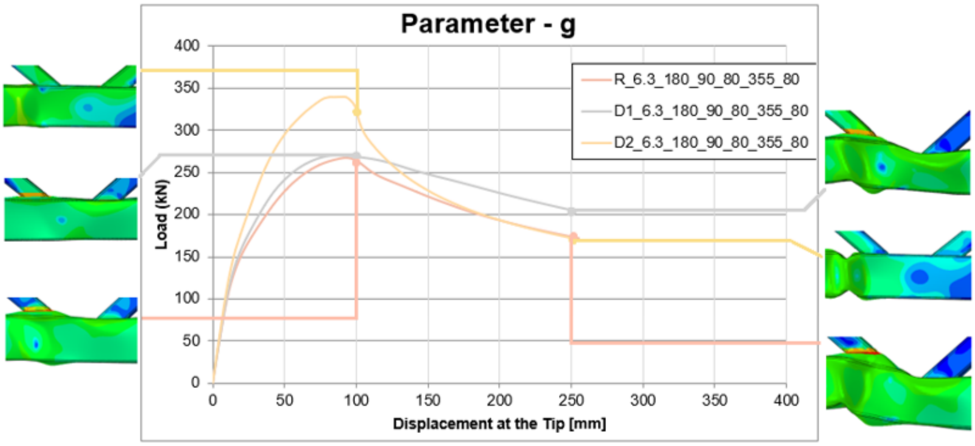
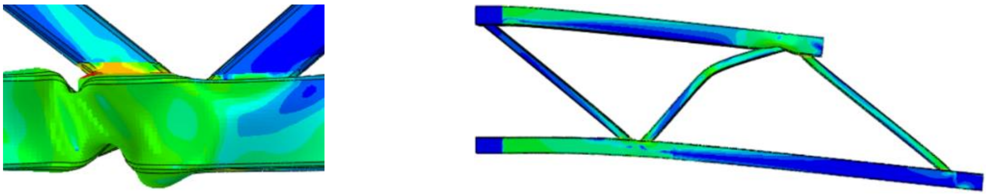


Figure 7: Influence of the joint detail in its deformation.



D1_5_140_90_80_355_0 **D1**_8_160_90_80_355_0

(a) (b)

Figure 8: Different failure modes.

Another relevant indicator of the influence of the type of joint detail applied is the resistance of the critical node itself. Focusing, for example, on model 6.3_180_90_80_355_80 and considering that the vertical displacement limit corresponding to node failure is $0.03\,d_0$, and thus 5.4 mm for a chord diameter of 180 mm, Table 3 was developed. It displays the node failure values for a D1 and D2 joint detail, as well as the percentage increase when compared to a traditional joint. Despite the results present in Table 3 indicating that the LCT type of detail did not have an impact on the node resistance, as referred before, they do increase the global resistance of the structure, as well as rigidity, more significantly for smaller values of chord thickness, bigger chord widths and gaps between braces and higher steel grades.

Table 3: Critical node resistance for model 6.3_180_90_80_355_80, and increased resistance, in percentage, from a regular detail to a LCT detail.

Joint detail	Node resistance [KN]	[%]
D1	178.36	- 0.34
D2	132.10	- 26.19
R	178.98	-

3. Case study

A simply supported Warren truss was designed to allow the study of the advantages in the use of an LCT detail. For S355 steel, Figure 9 displays the cross-section dimensions and truss geometry designed. A displacement of 84 mm was applied at the compressed joints along the top chord.

Since the upper chord is compressed, the nodes 1, 2, 5, 7, 9, 11, 13, 15 were constrained to prevent lateral displacements and maintain the out-of-plane chord buckling between the joints.

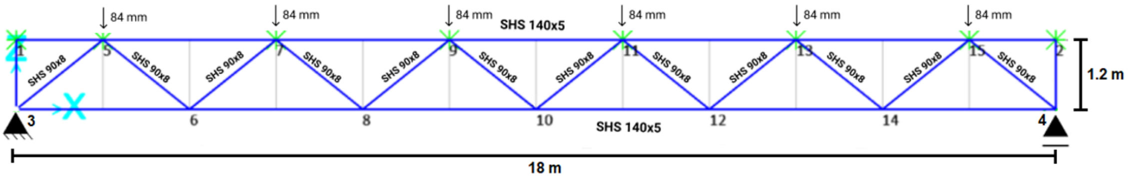


Figure 9: Designed truss to be studied.

Four models were studied alternating between a D1 and a traditional detail, as well as their position in the truss. Since it is in the manufacture of the structures that most cost and time are spent, the use of a gap simplifies the construction process in addition to facilitating the passage of equipment. Considering the relevance of joint gaps in a truss, it was concluded that, apart from evaluating the performance of D1 joints, it was relevant to study the effects of the gap on the behaviour of the truss. An eccentricity of 20 mm was applied to the truss with a D1 joint in the top nodes and a regular joint in the bottom ones.

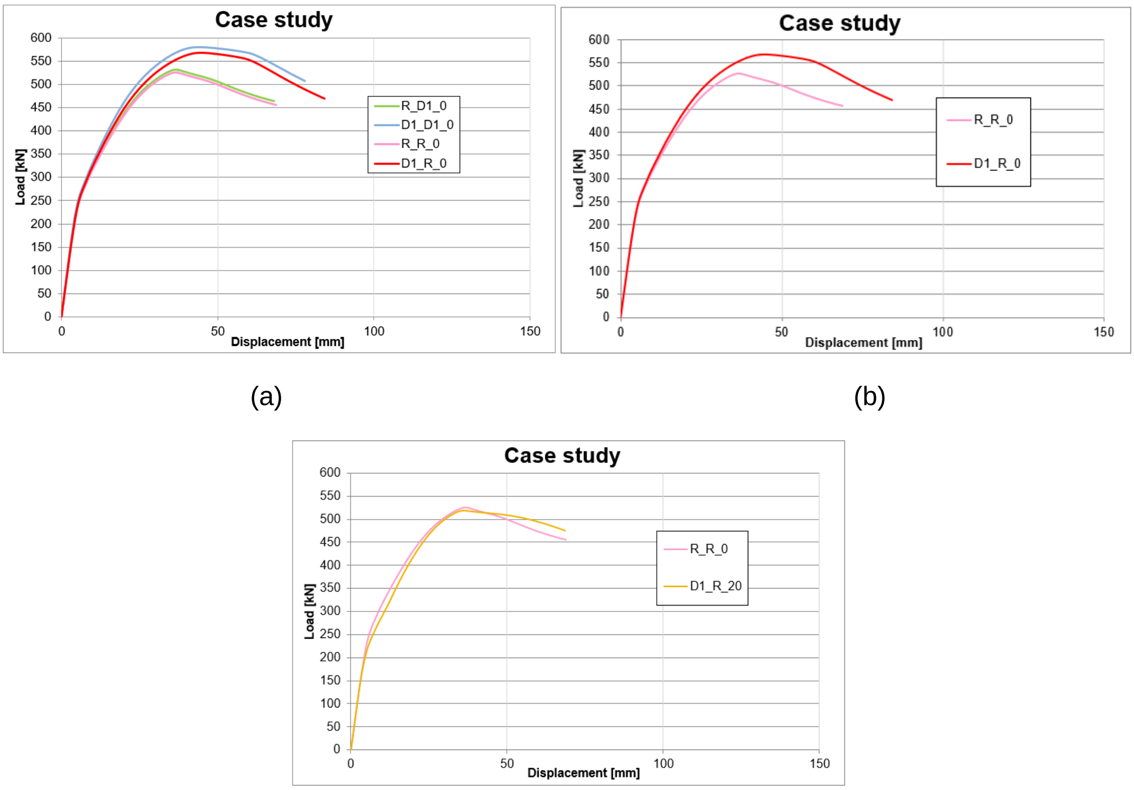
The modelling procedure, as well as the welds joint geometry and mechanical characteristics, employed in chapter 2, were also used to numerically model the present structure. No imperfections were introduced to the models and, to prevent out-of-plane displacements, the constraints applied to the upper connections of the structure followed the same modelling technique used in chapter 2.

Analysing the results displayed in Figure 10 (a) it is concluded that only the nodes in compression condition the behaviour of the structure since the models R_D1_0 and R_R_0 present a very similar behaviour. Therefore, there is no advantage in using the same geometry as model R_D1_0, where there is a detail D1 in tension. A D1 joint detail only significantly influences the peak load if it is in compression, as observed in the increase of the yield strength of the D1_R_0 model. Another conclusion that can be taken when comparing models D1_D1_0 and D1_R_0 is the advantage of the latter, which is assumed preferable for taking less time, labour and material in the fabrication process, reducing the overall truss construction costs, while still achieving similar performance and strength.

From Figure 10 (b), model D1_R_0 improves the behaviour of the structure, increasing 7.88% of its maximum load when comparing to the R_R_0 model, proving the benefits in the use of an LCT joint detail over a traditional joint.

Following the conclusion derived from the comparison between models R_D1_0 and D1_R_0, a gap was applied only to the nodes in compression. Given that, it is visible in Figure 10 (c) that, when comparing the models D1_R_20 and R_R_0, with a detail D1 it is possible to have a gap of 20 mm and obtain a similar ultimate load capacity as a structure with only regular joints. Thus, detail D1 allows one to increase the ultimate load or to have larger eccentricities but with the same yielding strength capacity as a structure with regular welded connections.

All the model studied in ABAQUS displayed a reasonable mid-span vertical displacement of less than L/180.



(a)

(b)

(c)

Figure 10: Comparison between models R_R_0 and: (a) R_D1_0, D1_R_0 and D1_D1_0; (b); D1_R_0 (c) D1_R_20.

4. Conclusions

The work presented allowed the fulfilment of the main objective of this dissertation, which is to conclude that the LASTEICON details, fabricated using laser cutting technology, substantially improve the global behaviour of the structure. In terms of resistance and stiffness, they present a more advantageous option when compared to conventional manufacturing techniques.

The parametric studies showed that a higher resistance and rigidity with LCT details, when compared to the regular ones, is achievable. Moreover, the decrease in chord thickness increases the influence the type of detail has on the truss resistance.

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Although few models were run in the parametric study with a D2 detail, it proves to be the most effective in increasing the global resistance of the truss, as expected, given that both braces penetrate the chord increasing the node rigidity. This significant increase of rigidity also leads to a failure mode outside the critical node.

As for the applicability of a D1 type of joint to a larger structure, the results confirmed the benefits of its use. Compared to the use of a traditional detail throughout the truss, the application of the LCT detail in the compressed nodes increases the ultimate load. Regarding the implementation of an eccentricity, an increase of the gap between the braces in the compressed joints, with a D1 detail, allows the same resistance as a structure with only regular joints and no gap. This allows for an easier construction process, lowering the fabrications costs and environmental impact while still achieving similar performance and strength. It is also worth highlighting that it is preferable to apply the LCT detailing only in the compressed joints rather than in the whole truss since, for similar structural behaviour, the overall truss construction costs decrease.

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