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ELASTIC BUCKLING BEHAVIOUR OF AEROSPACE CHS GUSSETED "T" CONNECTIONS

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Summary

Lightweight tubular structures are widely used in aerospace structures. Lattice beams are simple or gusset reinforced connections. As the gusset design offers a lot of solutions in aerospace, this paper focuses on the assessment of the elastic buckling of the most frequently used welded gussets of "T" connections. A FEM method was validated by analytic equations of a triangular gusset, and based on the results, conclusions and design recommendations are made.

Key words: *elastic buckling, aerospace, gusset, welded structures, finite element method*

1. Introduction

Latticed beams were the first structures successfully employed on early aircraft, allowing a compromise between strength, rigidity and volume for storage, all to achieve the minimum weight. Used in the primary structure (especially fuselage), engine mounts, landing gears or seats, the most used profiles are CHS (Circular Hollow Section) tubes.

Because of weight constraints, the wall thickness of tubes is kept to a minimum, thus, buckling is becoming a major design constraint. In order to improve the general buckling behaviour of members and to achieve a better stress distribution, joints are stiffened by using gussets. From the stability point of view, this may lead to local buckling problems. Because aircraft beams employ a large variety of gussets regarding dimensions, shape, placement or welding method, there is a lack of knowledge regarding the use of the most appropriate type of gusset according to application.

In the practical design, there are analytical methods or the finite elements analysis to check gussets, but there is no design homogeneity or standardization, even the major constraint is the same: maximum strength for minimum weight. For this reason, the design of connections differs between manufacturer, airplane and even design team.

This paper presents an assessment of simple and double gusseted "T" connections. This study is a part of a larger program developed by Nuarb Aerospace and the Transylvania University of Brasov, focusing on the sizing and the influence of shape and geometrical parameters on the CHS gusseted connection elastic behaviour and methods to decrease stress level by tubes topology.

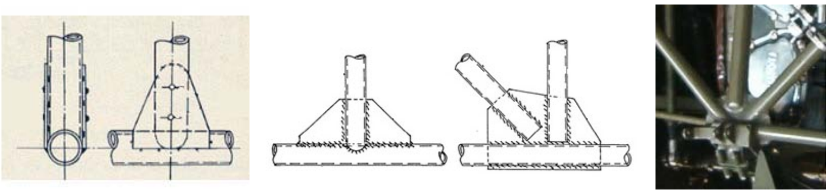
2. Gusseted "T" Connections

Gussets are used in the mechanical and structure steel design, in the civil, industrial and mining engineering areas. As specified in [7] and [1], gussets are used in beam to column and column to ground plate connections or to facilitate bracing or other attachments to rectangular hollow sections (RHS), as presented in [4], [9]. To improve the "T" connection fatigue behaviour, base plates (chord doublers) are employed [11], [15], [12] or outer collars are employed [1].

According to [5], the compressive behaviour of the gusset plate connection has received a limited attention. Thornton gave an expression of the critical buckling load of the gusset connected to the bracing [17]. In 2002, Yam and Cheng gave an analytic expression closer to test results [18]. Chou and Chen studied the elastic and plastic buckling behaviour of braced gussets [5].

Roeder et al. mentioned that the design of gusset plate connections to achieve the design objectives requires a significant effort which may not lead to an intended response [16]. Roeder proposed a balanced design procedure to improve the seismic behaviour of braced gusseted plate structures. Martin and Purkiss gave an analytical method for the calculation of the buckling stress of gussets, assuming the gusset to be composed of a series of fixed ended struts, parallel to the free edge [10].

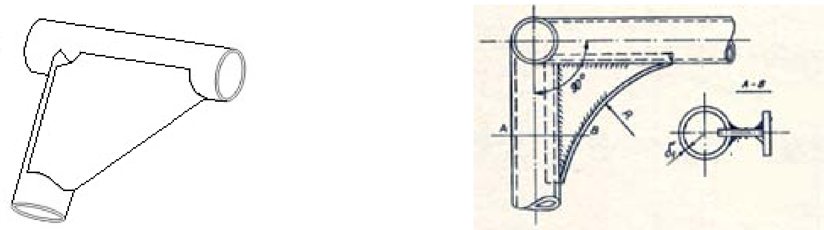
Gussets are used in aerospace welded structures in "T" joints or bolting areas to decrease the level of stress or to improve rigidity (Fig. 1). According to Niu, tapered gusset plates should be incorporated in all important welded joints to insure gradual changes in the stress intensity in members; also, gussets lessen the danger of fatigue failure by reducing the stress intensity [13]. Bruhn recommends gussets especially when connections are subjected to vibrations and loaded out of plane bending [3].



a) b) c)

Fig. 1 a) Twin gussets and radially inserted gusset [14]; b) Hole welded [8]; c) Gusseted node - SA315 helicopter [Deutsche Museum, Oberschleissheim]

Blodgett recommends the use of tangentially placed gussets, because a radially placed gusset leads to brace cracks at the gusset margins [2]. Blodgett also recommends the use of gussets with care, because the rigidity added to the connection may lead to member's failure [2]. Duggal recommends curved free margins of the gusset to decrease the stress level in members [6]. In order to improve buckling behaviour, the free edge of the gusset may be flanged by forming, bending or welding (Fig. 2).



a) b)

Fig. 2 a) Closed gusset ("U" shaped section) [19]; b) Welded flange gusset [8]

2.1 Methodology

In literature on CHSs, tubular joints are calculated for three load cases: axial load (AXL), in plane bending (IPB) and out of plane bending (OPB). For the gusset buckling behaviour only the IPB will be considered (Fig. 3).

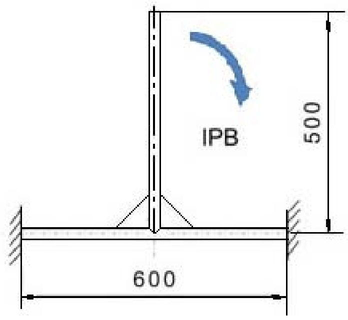


Fig. 3 "T" connection dimensions and load type

The usual "T" connection (90^0 between members), with the member's diameter of 25 mm and wall thickness of 1.0 mm, both for tubes and gusset, was considered. The chord (the horizontal tube) is 600 mm in length, while the brace (the vertical tube) is 500 mm in height (Fig. 3). Plane dimensions of a typical twin gusseted joint are shown in Fig. 4.

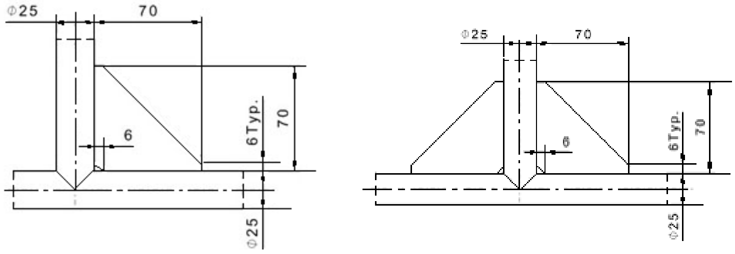


Fig. 4 The studied "T" connection with simple and twin placed gussets typical dimensions

All the gusset shapes studied within this study have the dimensions as shown in Fig. 4.

In order to check the FEM methodology, an analytical stress calculation and a FE model were made for the same dimensions of the triangular plate planar loaded, corresponding to the fixed edge condition (Fig. 5b).

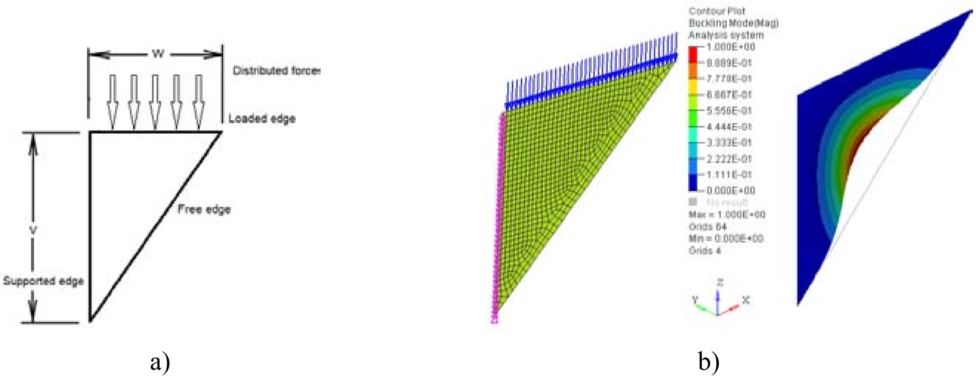


Fig. 5 a) Triangular plate planar loaded [20]; b) FEM model of undeformed and deformed triangular plate (fixed edge)

According to [20], the elastic buckling stress for a triangular gusset (Fig. 5a) is given by:

$$f_b = K \cdot E \cdot (t/w)^2, \tag{1}$$

where:

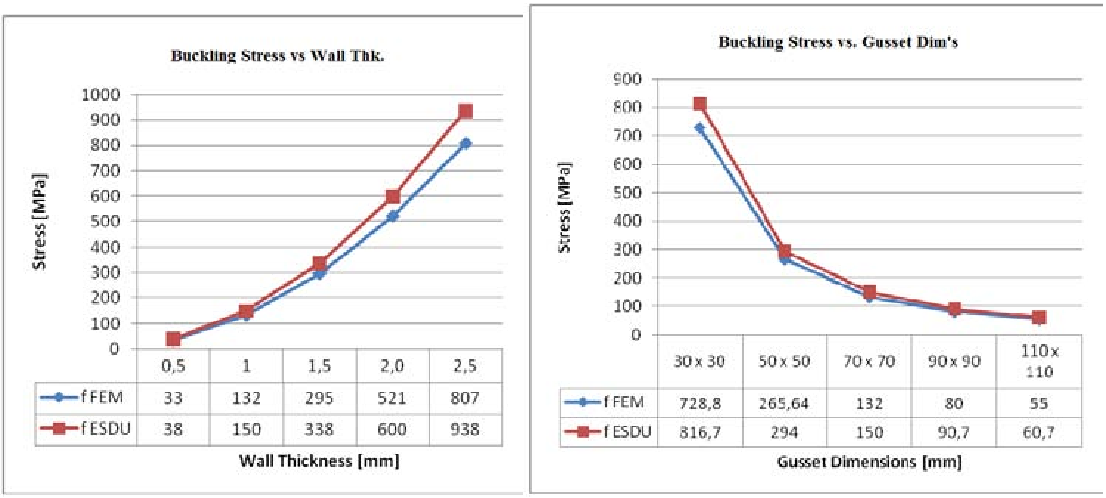
E	the modulus of elasticity of the material;
f_b	the elastic buckling stress;
t	the wall thickness;
w, v	the length of the sides of the triangular plate;
K	the buckling stress coefficient; K depends of the boundary conditions of the edges as follows (w/v = 1): K = 3.50 for the fixed edges (embedded) and K = 0.52 for the simply supported edge (pinned).

In the analytical calculations, the fixed edge hypothesis was used, corresponding to the welded edge of the gusset to the tube.

The FE software used was Hypermesh / Radioss. Quad shell elements with 2.0 mm in mesh size were used. Boundary conditions were embedded (all degrees of freedom restrained) for the chord (corresponding to the welded end) and free for the brace. Load was introduced from the free end of the brace. Material used was a low alloyed steel with ultimate tensile strength of 980 – 1080 MPa, Poisson's ratio of 0.3 and Young Modulus E = 2.1E5 MPa.

The method excludes the effects related to fabrication such as the configuration of the weld (flat, convex, concave) and the local condition of the weld toe (radius of the weld toe, undercut, etc.). The welds are polished full penetration butt welds and no factoring of the FE predicted stresses to account for stress concentrations associated with the cross sectional weld geometry or weld defects was applied.

Fig. 6 presents the buckling stress from the analytical calculations vs. FEA results for different triangular plate wall thickness and dimensions. For the buckling stress variation over the wall thickness, the errors were between 12 – 14%. For the buckling stress variation over the plate dimensions, the errors were in the range from 10 – 12%.



a) b)

Fig. 6 Analytical and FEA calculations results for: a) buckling stress vs. triangular plate wall thickness; b) buckling stress vs. triangular plate dimensions

For the simply supported edge the FEM verification with the analytical calculation only for the 70 x 70 x 1.0 mm plate was made. The difference was of 1.2%, which, together with the value from the fixed edge condition, was considered acceptable for studying the elastic buckling of different shapes of gussets by means of the FE analysis.

All joints were subjected to the IPB load (as presented in Fig. 3) in order to find the critical buckling load.

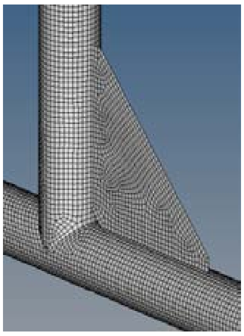
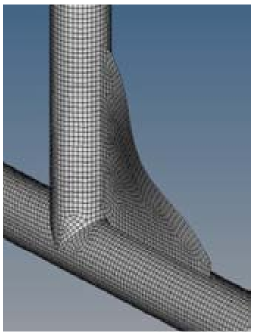
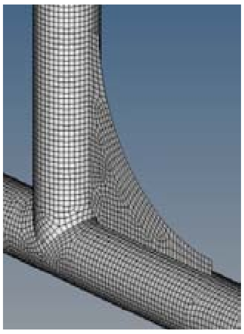
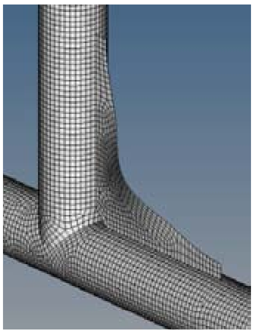
2.2 Gussets used for the study

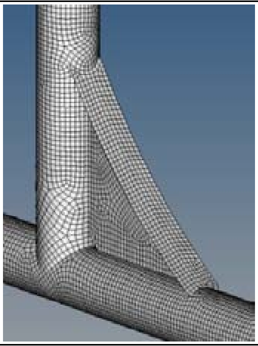
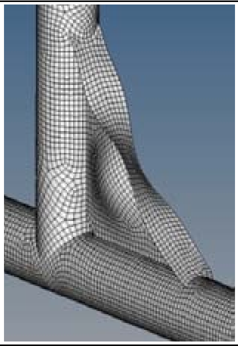
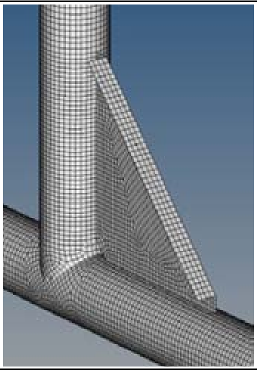
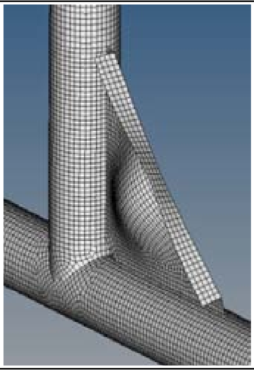
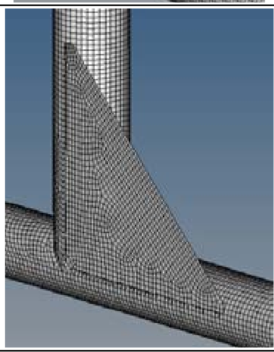
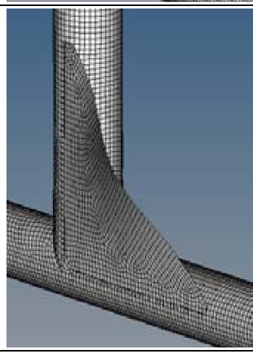
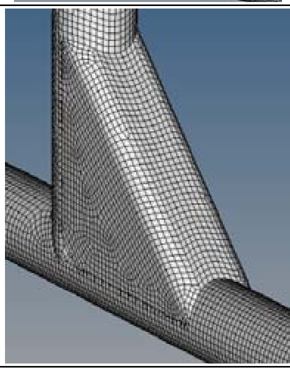
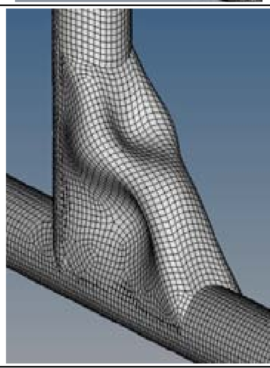
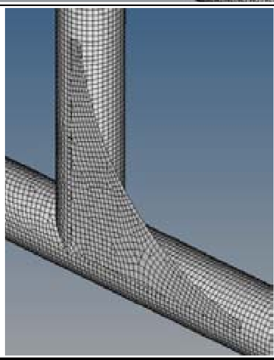
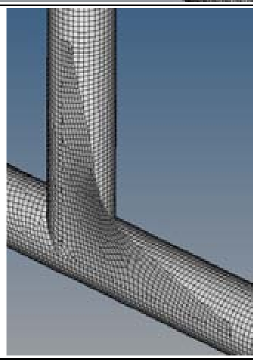
As usual, the sizing of a joint is made subject to the static requirements. After the structure is designed, buckling calculations are made only for checking purposes. For the conceptual design, it is useful to have a quantitative assessment of buckling behaviour of different gusset shapes, in order to help designer to select the lightest solution for the highest rigidity. In the present study, a number of gussets used in primary or secondary aerospace structure design, as listed in Tables 1 and 2, were selected.

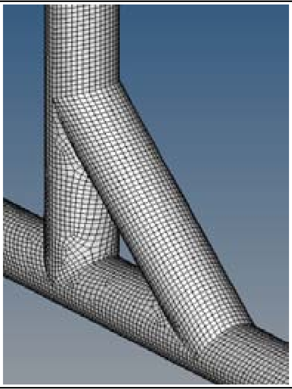
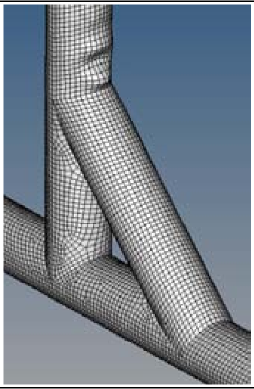
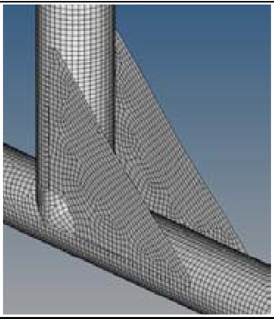
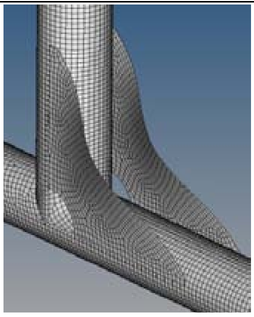
Gusset A is commonly used. Gusset B was created to decrease the level of tension in tubes (especially in the brace). Flanged Gusset C is used especially where the gusset can be subjected to buckling. Gusset D is identical with A, but tangentially placed to the tubes. The double gusset E is used especially for heavy loaded joints, being welded to tubes on the whole of the contour. Gusset F is similar with B, but tangentially placed. Gusset G is used when a fast and cheap solution is needed, replacing a sheet metal gusset with a tube. Gusset H is used when the in plane bending load is significant.

Gusset M has a triangular shape, tangentially placed to the joint members. Double tangentially placed gussets need a particular attachment to the brace. Used in engine supports, gusset M has a vertical slot to allow welding onto the brace. Gusset N is similar with M, keeping the material continuously in the brace area and welds being applied in holes. This gusset is a variant of M, with lower manufacturing costs. Gusset O is radially placed, inserted in the symmetry plane of the connection (members are slotted). This gusset is used in heavy loaded structures or in hard points (points of external attachments or fittings). Gusset P is radially placed, inserted in the symmetry plane of the connection. The brace is not in contact with the chord, having a formed end in order to connect the whole section of the tube to the gusset. This type of gusset is used for planar connections with multiple braces. Gusset R employs two triangular gussets radially and symmetrically placed. Gusset S uses two triangular gussets tangentially placed.

Table 1 Single (side) gusset codification

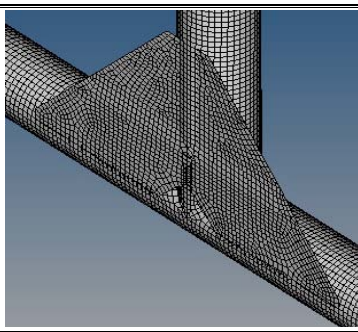
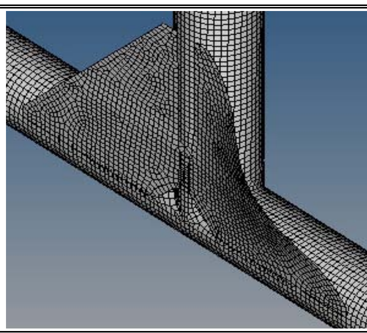
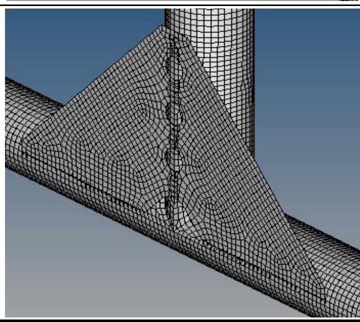
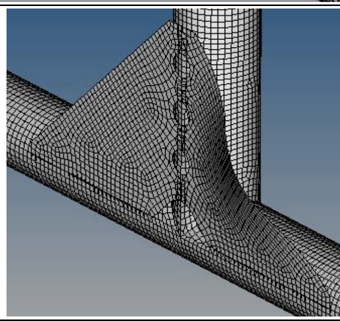
Gusset Code	Shape/ Position	Undeformed Shape	Deformed Shape
A	Triangular/ Radial		
B	Curved Triangle/ Radial		

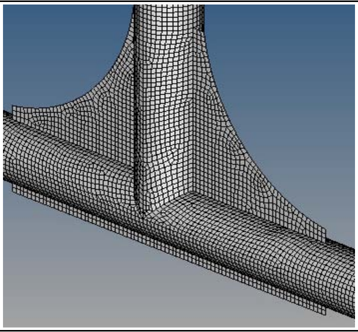
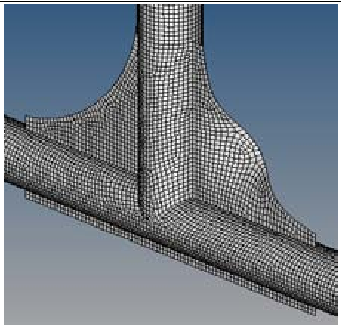
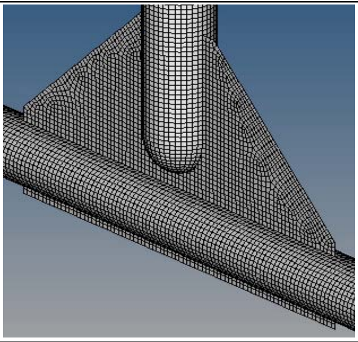
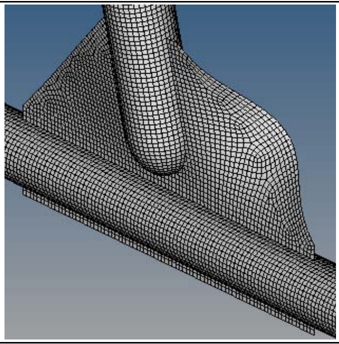
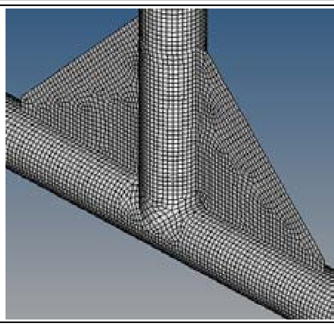
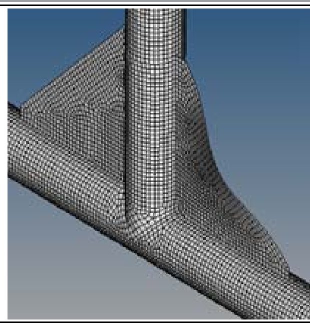
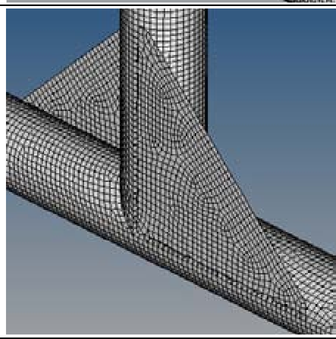
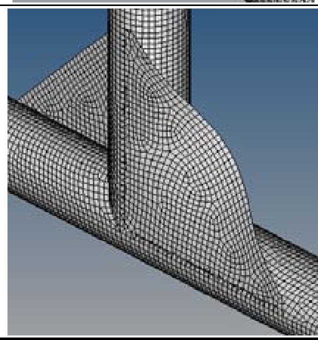
Gusset Code	Shape/ Position	Undeformed Shape	Deformed Shape
B FL	Flanged Curved Triangle/ Radial		
C	Flanged Triangle/ Radial		
D	Triangle/ Tangent		
E	Double Triangle Bent/ Tangent		
F	Curved Triangle/ Tangent		

Gusset Code	Shape/ Position	Undeformed Shape	Deformed Shape
G	Tube/ Radial		
H	Triangle Bent/ Tangent		

From Table 1, it can be seen that most of gussets deflect in the same manner, specific to the first buckling mode (the buckling length is equal to a half of the wave length). A particular behaviour is seen on the E gusset, the buckling length being equal to the wave length. Gusset G (tubular gusset) presents also a specific buckling mode as local buckling of the vertical member.

Table 2 Double (twin) gussets codification

Gusset Code	Shape/ Position	Undeformed Shape	Deformed Shape
M	Slotted Triangular/ Tangentially placed		
N	Triangle with holes/ Tangentially placed		

Gusset Code	Shape/ Position	Undeformed Shape	Deformed Shape
O	Curved free edge/ Radially inserted		
P	Triangle (tubes not in contact)/ Radially inserted		
R	Twin triangles/ Radially placed		
S	Twin triangles/ Tangentially placed		

The buckling of double gussets is very similar for all gussets, being intuitive and with no exceptions.

3. Discussion

In order to make an assessment of the studied gussets, the critical buckling load was normalised with the critical buckling load of the A type gusset (value for the A Gusset is 1.0). The results are presented in Fig. 7.

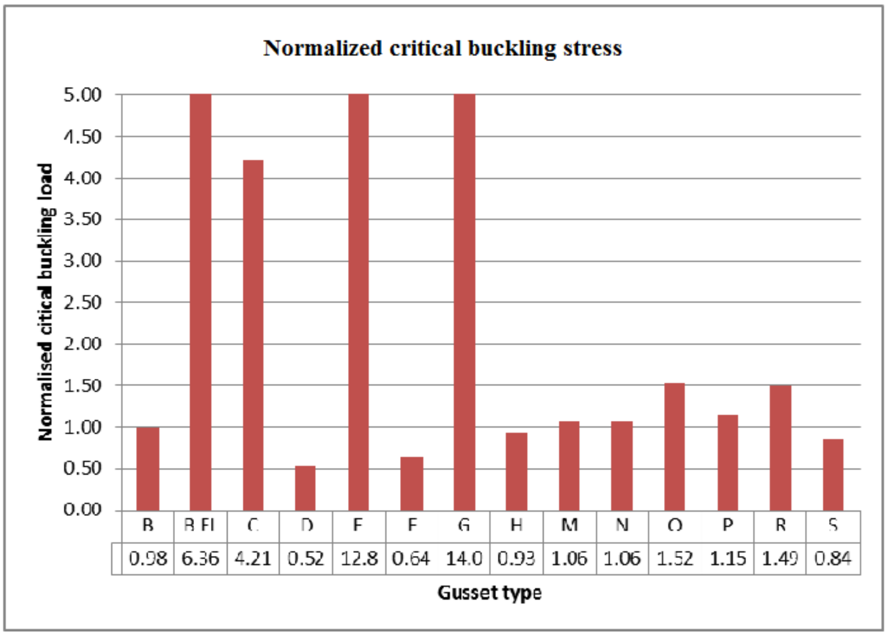


Fig. 7 Normalised critical buckling load for studied gussets

The rigidity of the gusset is proportional to the normalised critical buckling load.

From Fig. 7, it can be seen that the gussets with free edges have values in the same range, while the flanged edge (B Fl & C) are 4 to 6 times stiffer. A special case is represented by the closed gussets E and G, as the stiffest solutions. Simple gussets radially placed are about two times stiffer than those tangentially placed, because of the asymmetric loading of the latter.

Double gussets are not significantly more rigid than simple radial gussets, except for the inserted gusset O and the double radially placed gusset R. Double tangentially placed gussets are almost of the same rigidity as simple radially placed gussets, even though they are two times heavier.

The designer's task is to find the best compromise between many parameters. After stress parameters, it is important to consider weight (simple gussets are preferred) and manufacturing costs. From this point of view, straight free edge gussets are the cheapest, followed by curved free edge and flanged gussets.

Another important parameter is the inspectability (to allow the detection of cracks), whereby the E gusset is not preferred. The placement of gussets has to be such that the weld will be shear loaded and not tensile loaded. Based on this criterion, tangentially placed gussets are preferred.

4. Conclusions

Lightweight lattice beam members of aircraft structures are subjected to buckling. For this reason, the stability behaviour of different shapes of gussets is important to be known already at the conceptual design phase.

As it is found, there are big differences between the categories of the employed gussets: flanged gussets are 4 – 6 times more rigid, while closed gussets (hollow sectioned E and G) are 12 – 14 times more rigid. Formed gussets (E & H) are the most expensive gussets.

Simple (side) radially placed gussets exhibit almost the same rigidity as double gussets. From the buckling point of view, double gussets employment is not justified (because of the added supplementary weight). From the fatigue point of view, radial gussets have tensile loaded welds, leading to poor behaviour.

The most usual gusset, the D type, is the shape with the worst buckling behaviour. If it will be used in joints subjected to buckling, it is preferable to be replaced with gussets of the M or N type.

The final decision related to the employment of a type of gusset has to be made by taking into account not only buckling, but also static behaviour, weight, manufacturing costs and maintainability conditions.

By improving the bending and buckling behaviour of members, the employment of gussets can lead to a smaller section needed for members, leading to lighter structures. Further research will be done so as to facilitate the sizing of CHS connection gussets and the calculation of weight savings in a lattice beam by using gusseted connections.

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