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THE FINITE ELEMENTS ANALYSIS VS. EXPERIMENTAL BUCKLING BEHAVIOR OF THE THINWALLED PLANE GUSSETS

G. Dima[1], H. Teodorescu- Drăghicescu[2]
[1]Transylvania University, Brasov, ROMANIA, dumitru.dima@unitbv.ro
[2]Transylvania University, Brasov, ROMANIA, draghicescu.teodorescu@unitbv.ro

Abstract: *The lightweight tubular latticed beams are used in aerospace structures as well as in civil engineering applications. Depending of manufacturer, gussets may be used to increase the stiffness and rigidity of the beams. As a continuation of previous researches to obtain lighter structures by using gussets, this article presents the results of a research regarding the plane gussets buckling. Using analytical, finite elements calculation and experimental testing, the buckling behavior of tubular T joints reinforced with gussets was studied. The experimental testing was made for gussets subjected to both compression and tensile loads. The gusset buckling was analyzed together with the joint members failure, conclusions and design recommendation being made.*

Keywords: *aerospace, buckling, welded structures, gusset, finite element analysis*

1. INTRODUCTION

Aircraft structures has to comply with two major contradictory constraints: to withstand to in flight and landing loads, for a minimum weight. Being used from the beginning of the aviation industry, latticed beams was one of the most extensive employed structure on aircraft because its functionality, reliability and low manufacturing costs. Many materials, joining techniques and layouts were used up to 1935 – 1940, when monocoque structures finally demonstrated their superiority, for affordable manufacturing costs.

Loads carrying structure whose failure leads to a catastrophic event is called primary structure. Latticed beams were employed as primary structure for wing and fuselage, having circular section tubes as members. Under the constraint of the minimum weight, all structures are thinwalled, one of the main failure mode being the lose of stability.

In order to decrease the structural weight, previous researches were done to replace the beams with bracing (Pratt and Warren) with beams free of bracing (Vierendeel) [6]. In order to decrease the stress level in joints area and to increase rigidity, the Vierendeel beam were reinforced with gussets. Even from static, dynamic and fatigue point of view, the effect of adding gussets was studied, the local buckling of gussets remained a concern.

This article presents the results of a research regarding the tubular latticed beam gussets. Theoretical and experimental researches were done on joints reinforced with gussets. Both theoretical and experimental studies conducted to conclusion that the gusset buckling occurs only after the failure of beam members.

2. BEAMS REINFORCED WITH GUSSETS

In the design of aircraft welded structures, the main task is to obtain a structure presenting details with the lowest stress concentration factor (SCF). This target allows longer fatigue life and lighter structures.

The tubular welded structures are met in automotive and civil engineering as well. In aerospace, the verification of the structures consists in weld seams static assessment and members buckling. For civil engineering, due to the dimension of the structures and members, the stress concentration factors are calculated with more accuracy, considering also stress distribution in joint area.

In literature there are presented a lot of solutions to decrease the stress concentration factors (SCF) as inner diaphragm, external collar [1], chord doublers [2], simple or double gussets [3], [4]. Other solutions consist in tubular structures with formed end tubes for brace, longitudinally or transversal placed [2], [5] and [8].

There is no unified theory of gussets shape and placement available, a lot of solutions being met on different aircrafts and manufacturers, gussets being external attached or inserted in joint members [9], [10].

In civil engineering (crane booms, offshore platform, masts) gussets are used in *T* or *K* joints to decrease the stress concentration factors. Reference [11] presents significant stress reduction in *K* joints using gussets inserted in the plane of joint, for axial load, in plane and out of plane bending. In reference [12] there are presented the effects of using gussets vs. the reinforcement of joint with chord doublers and brace collar, finding that the gussets provide a lower stress level in joint.

Recent researched were done to asses different shapes and placement of double and simple gussets [7]. Figure 1 presents few types of the analyzed gussets. In figure 2, one may see gusset *D*, which is very usual, has the lowest critical buckling load. Therefore, if gusset *D* does not lose stability under beam loading, therefore all other gusset shapes will be buckling proof.

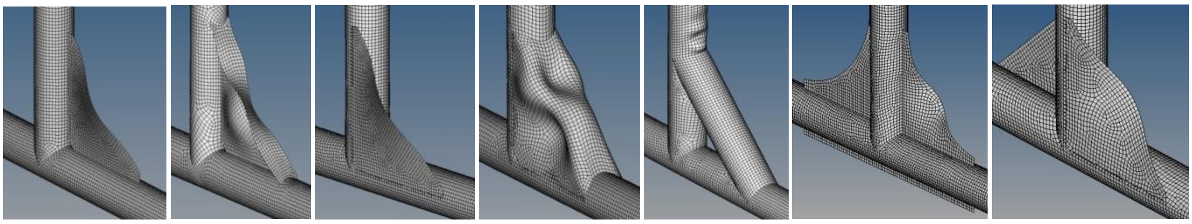


Figure 1: Different shapes of buckling analyzed gussets (*A/ B Fl/ D/ E/ G/ O/ S*) [7]

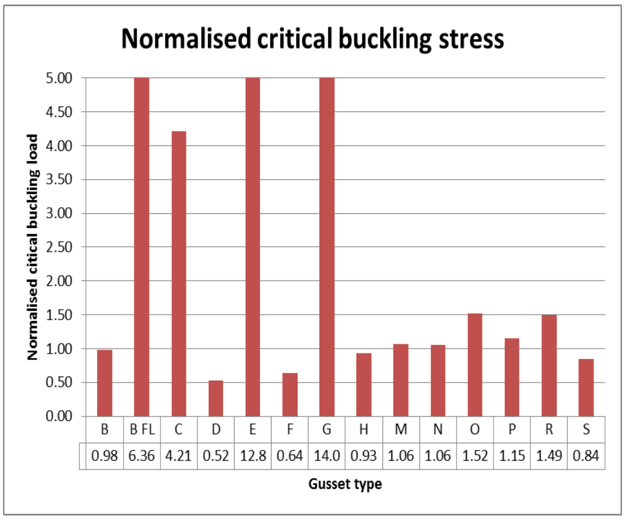


Figure 2: Different gussets buckling assessment [7]

3. THE FEA VS. ANALITICAL RESULTS OF TRIANGULAR PLATE SUBJECTED TO COMPRESSION

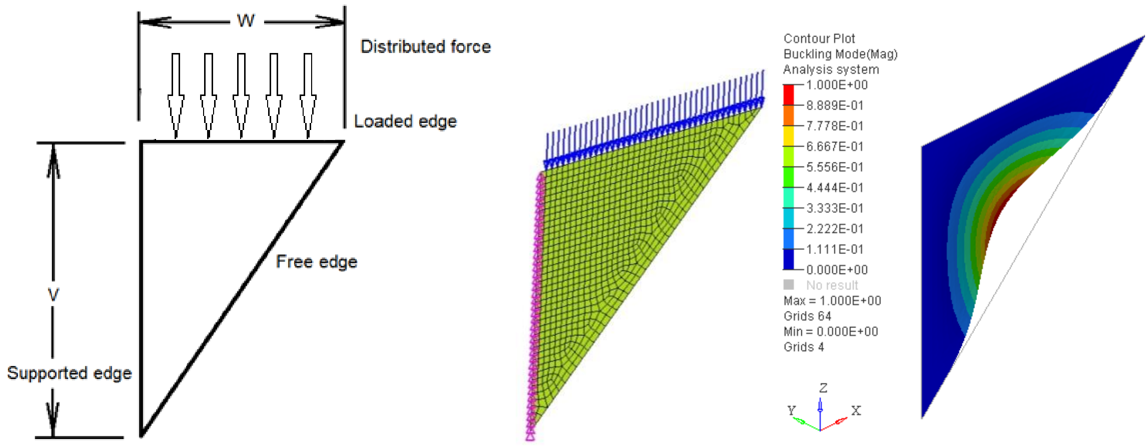
According to experimental studies from [13], the elastic buckling stress for a triangular gusset (Fig. 3. a) is given by:

$$f_b = K \cdot E \cdot (t/w)^2,$$

with *K* factor related to boundary conditions of edges as follows (*w/v = 1*):
K = 3.50 for fixed edges (embedded) and

K = 0.52 for simple supported edge (pinned).

In order to asses numerical finite elements (FE) solutions vs. analytical calculations, a FE model was generated. Plate dimensions are in a range of 30 x 30 ÷ 110 x 110 *mm*, with the wall thickness of 0.5 ÷ 2.5 *mm*. The material is low alloyed steel, with ultimate tensile strength of 980 – 1080 *MPa*, Poisson ratio of 0.3 and Yield Modulus E = 2.1E5 *MPa*. All boundary conditions are corresponding to the fixed edge condition (Fig. 3).



a) b)

Figure 3: a) Triangular plate planar loaded [13]; b) The FE model and the deformed plate [7]

The analytic calculations used the fixed edge hypothesis, corresponding to the welded attachment of the gusset to the vertical member of joint. A commercial software solution was used (Altair Hypermesh/ Radios 10). The FE model consists of a 2D shell mesh, with the mesh size of 2.0 *mm*. Weld geometry was not taken into consideration. The FE model has all degree of freedom restrained on vertical edge and all degree of freedom unconstrained for the horizontal edge. Vertical load was distributed on horizontal edge's nodes of the model.

With results obtain from FE analyses and analytical calculation according [13], graphs for geometrical parameters over triangular plate stability behavior were raised. For different wall thickness, the differences are in the range of 12 ÷ 14% (Fig. 4. a). For different plate dimensions, the gaps are in a range of 10 ÷ 12% (Fig. 4. b).

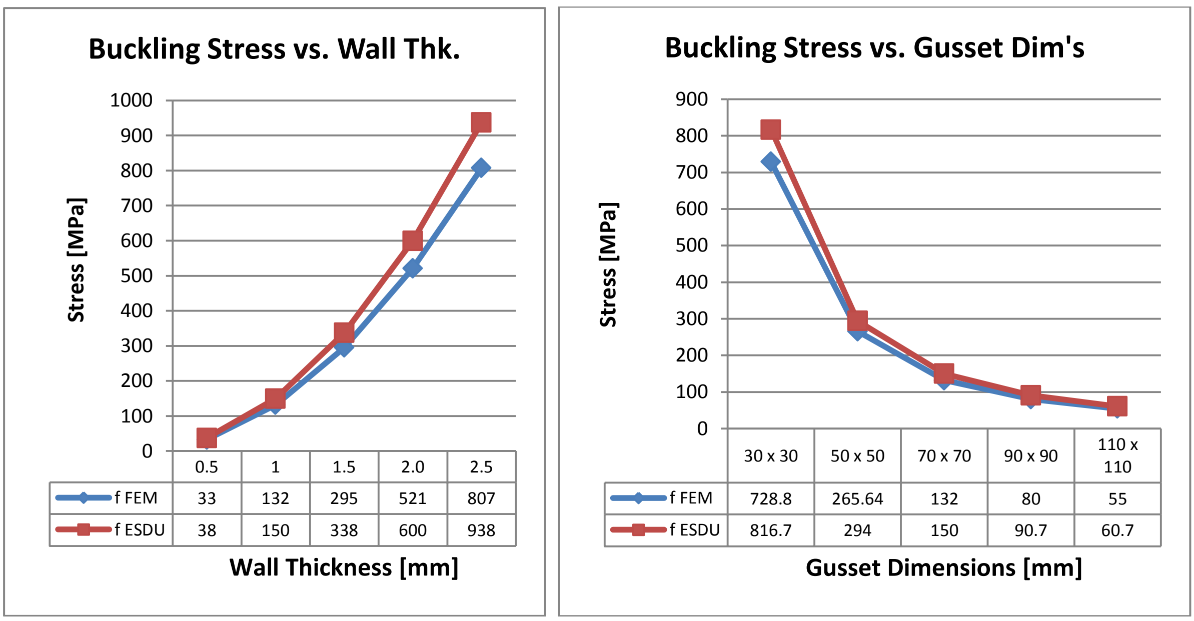


Figure 4: Analytical vs. FE calculated buckling stress for different: a) Plate wall thickness;

b) Plate dimensions [7]

In figure 5 one may see the FE vs. analytical critical buckling force for different gusset dimensions ratio. For ratio of 1.0, the first buckling mode occurs. For ratio values different of 1.0, gussets buckling correspond to one of superior buckling mode [12]. Thus, for 0.4, 0.5 and 1.2 ratios, the second buckling mode was considered. For ratio of 2.0 and 2.5. the third and the fifth buckling modes were considered respectively. For up to 1.5 ratio value, the differences are below 12%, while for other ratio values, the differences are growing up to 22%.

Considering all above, one may formulate the conclusion that FE and analytical calculation of critical buckling stress presents good similarities.

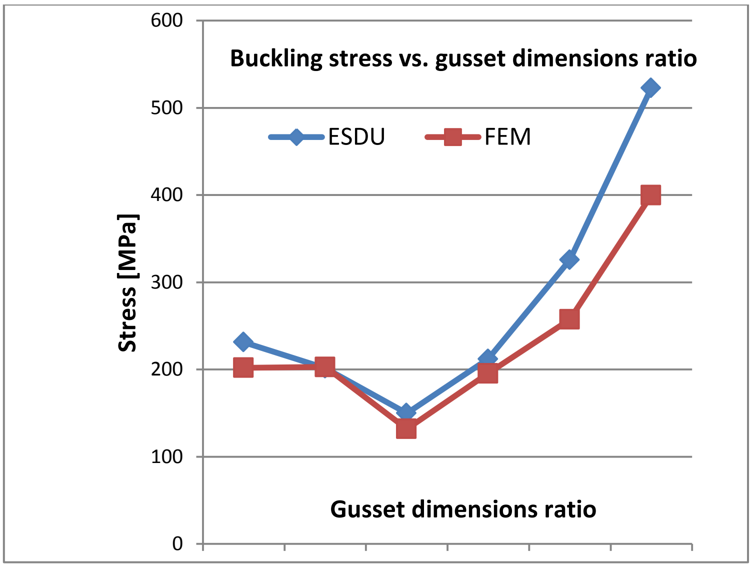


Figure 5: a) Analytical vs. FE calculated buckling stress for different gusset dimensions ratio

4. THE FEA VS. ANALITICAL RESULTS OF A JOINT GUSSET SAMPLE SUBJECTED TO COMPRESSION

For experimental results, a sample made of steel tubes with 22 *mm* diameter and 2 *mm* wall thickness was considered. Dimensions of gusset are 80 x 80 x 2.0 *mm*, gusset being tangent placed to the joint members (Fig. 6).

According to graphs shown in figure 4 b, for a 80 x 80 x 1.0 *mm* gusset (made from OL37 STAS 530/1) the critical buckling stress is 120 *MPa*. In figure 4 a, for a 2.0 *mm* gusset, the critical buckling load is four times bigger (also the inertia momentum is four time bigger), therefore, the critical buckling stress for the 80 x 80 x 2.0 *mm* gusset will be 120 x 4 = 480 *MPa*. Considering that the allowable stress values for OL37 steel are σ_{tu} = 370 *MPa* / σ_{ty} = 240 *MPa*, the conclusion is the joint members will fail before the gusset buckling.

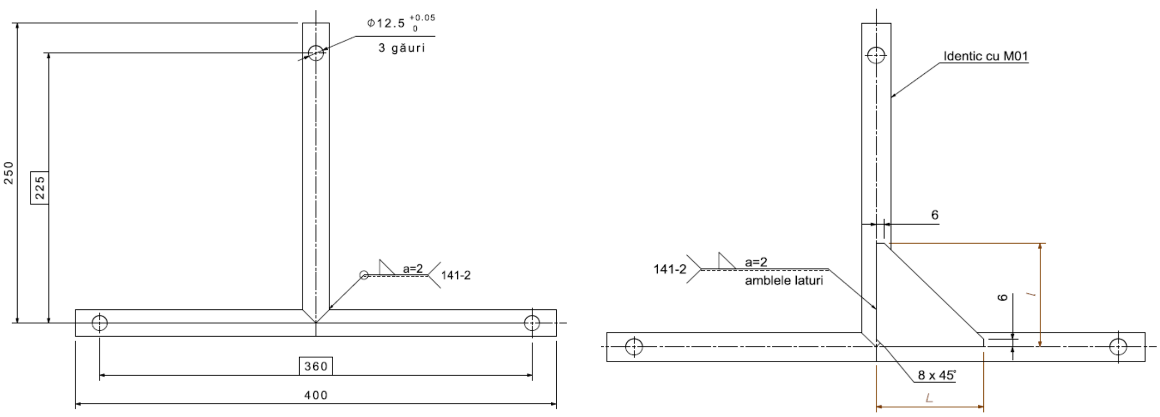


Figure 6: The dimensions of the joint members and the gusset sample

The FE analysis revealed a 0.97 *kN* bending load for a value of 240 *MPa* for the Von Misses stress in joint members (Fig. 7 a). This load, generates a 220 *MPa* von Misses stress in gusset, which is far smaller than the previous calculated 480 *MPa* critical buckling stress. Therefore, the joint's members plastic failure will occur before the gusset buckling. The FE analysis loads are 7.5 *kN* for the first buckling mode, and 9.8 *kN* for the second buckling mode respectively (Fig. 7 b & c). The conclusion is analytical calculations and FE analysis lead to the same conclusion related to static vs. buckling behavior of the joint gusset sample.

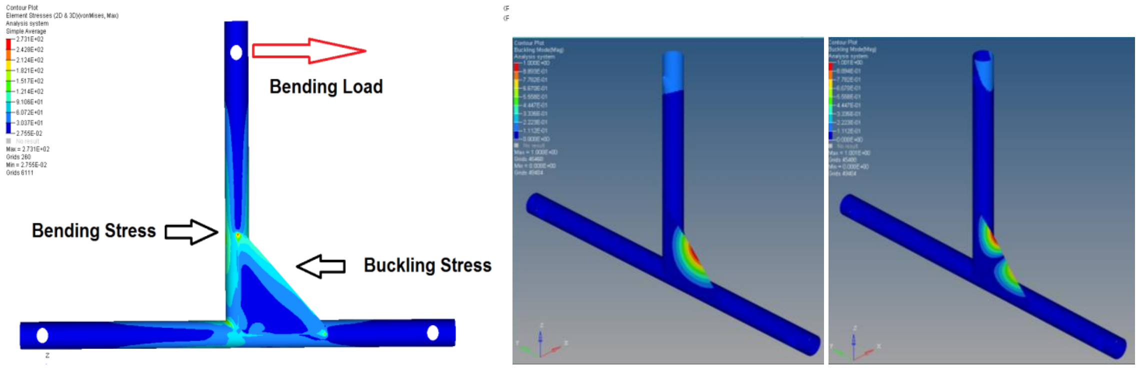


Figure 7: FE analysis results: a) static stress distribution; b) first, and c) the second buckling mode

5. THE EXPERIMENTAL TESTING

For experimental testing four samples were considered (Fig. 8 a). In order to assess the compression vs. tensile behavior of the joint gusset, two samples were subjected to tensile and two to compression loading. For mounting in an universal testing machine, an interface was used (Fig. 8 b, c). For compression/ tension loading of sample, same interface was used with different mounts of sample (gusset upward and downward, respectively). All tests were conducted up to the total failure of the samples. All the deformations phases and failure were registered.

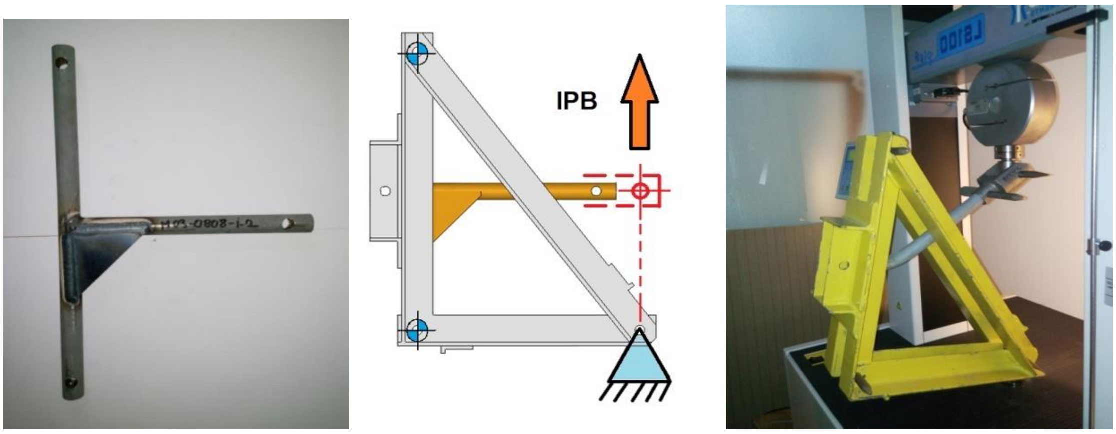


Figure 8: a) Test sample; b) Loading diagram c) Machine interface (yellow)

The tensile loaded gusset samples presented the initial deformation of the vertical member in the vicinity of gusset. Only after the total deformation of the tube section, the gusset free edge started to stretch. The second fail was in the upper margin of the gusset weld seam. After that, came the complete failure of the weld seam, the joint vertical and horizontal members coming to close contact (Fig. 9).

The compressed gusset sample presented the initial deformation of the vertical member in the same area as the stretched gusset. After vertical member complete deformation, the gusset started to lose stability until the vertical and horizontal tubes of the joint come to close contact (Fig. 10).

Therefore, both compression and tensile samples failed in the same manner, the tubes being less strength than the gusset. it is important to emphasize that the compression gusset welds remained intact even after total failure of joints, while for tension gusset the weld seams presented a total failure (Fig. 11 – note one tensile sample were not conducted to total failure for the better identification of the fracture initiation).

Figure 9: Joint gusset sample tensile testing

Figure 10: Joint gusset sample compression testing

Figure 11: Tensile and compression subjected joint gusset samples

6. EXPERIMENTAL RESULTS & DISCUSSIONS

All Load/ Deformation graphs were similar, with a long plastic range, corresponding to vertical tube rotation (Fig. 12 a). Curves are very similar for all four samples (Fig. 12 b) presenting the yield stress of 1.0 *kN* for three samples and 0.8 *kN* for one sample. The bending moment will be:

$$M_b = F_b \, x \, b = 1.0 \, kN \times 145 \, mm = 1.45 \, E^5 \, Nmm$$

The inertia modulus of the vertical tube is:

$$W_y = (\pi/32D) \times (D^4 - d^4) = 576 \, mm^3$$

Therefore, the bending tensile at the vertical tube contact with the gusset will be:

$$\sigma_b = M_b / W_y = 252\ MPa$$

From figure 12, the buckling load is within the range of 7.5 ÷ 8.0 *kN*.

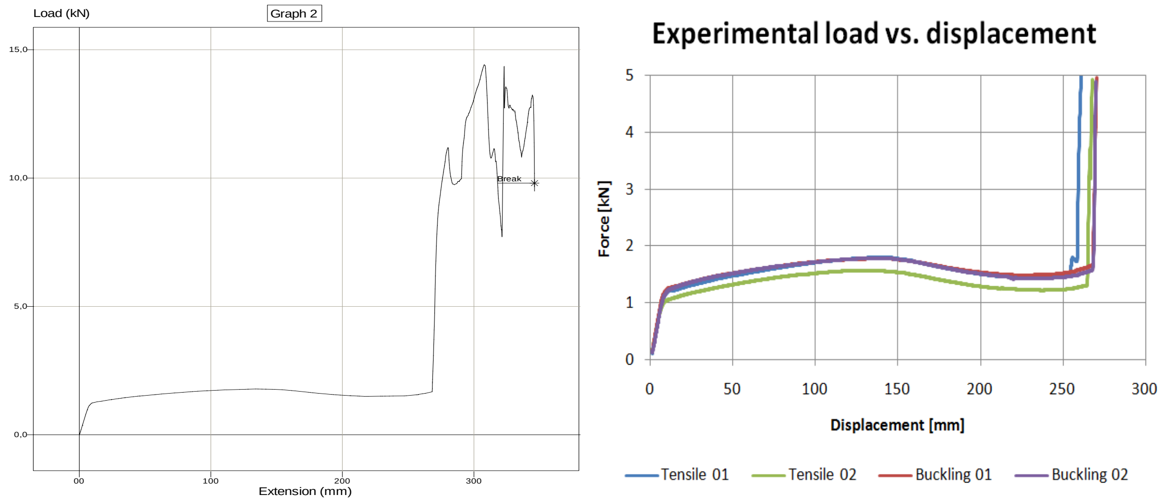


Figure 12: Load/ deformation graphs for all samples

7. CONCLUSIONS

Paper presented a numerical and experimental assessment of planar gussets used to increase the stiffness of the lightweight tubular latticed beams. The main conclusion of this research are:

- The finite elements analysis results comply with the ESDU theory for the triangular plate buckling.
- The experimental, FE analysis and analytic results are very similar.
- For a gusset with the same wall thickness as tubes, buckling occurs only after joint’s members failure. A research worth to be continued is to consider thinner gussets, in order to determine the thickness where the gusset will fail very close to the failure moment of the joint tube. This gusset thickness will be limited by manufacturing considerations (welding assembly is reccomended between parts with thickness ratio of maximum 2:1).
- The buckled gusset welds are more stiff than those of the tensile subjected gusset. This conclusion is important for structures calculated to preserve a certain structural integrity after failure (for instance those who need to preserve an minimum inner volume).
- For structural limit integrity, compression gussets are more recommended than tension gussets. Even this is not an intuitive behavior, this conclusion was demonstrated by experimental testing
- The gussets may increase stiffness of latticed beams with minimal added weight, without the risk of buckling. Therefore, for lightweight reasons, the Pratt beam could be replaced by the Vierendeel beam just adding corner gussets.

Actual and future research are focused to the dimensions, shape and placement of corner gussets to decrease the stress concentration factor in joints.

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