# ANALYSIS OF SANDWICH T-JOINTS UNDER COMPRESSION LOADS IN MARINE APPLICATIONS

Çiçek ÖZES[1*], Özgen AYDIN[2]

[1] Dokuz Eylul University, Faculty of Engineering, Department of Mechanical Engineering, Bornova, 35100- Izmir-TURKEY
[2] Izmir Regional Directorate of the Undersecretariat for Maritime Affairs, Atatürk C.128, Alsancak-İzmir, TURKEY,

*Author to whom correspondence should be addressed
E-mail: cicek.ozes@deu.edu.tr,

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**ABSTRACT**

This paper deals with the analysis of sandwich T-joints in terms of buckling loads, which are used in marine applications. Buckling loads have been investigated experimentally and numerically. Loading is applied as uniform axial compression. The GRP/PVC sandwich composite T- joints have been manufactured in six different geometries. Numerical and experimental results both show that the geometry of the T-joint area affects the buckling loads. It has been observed that failure mode is the same in all of the joint types, which is core shear. Stress distributions in T-joints have also been investigated under buckling loads and also for a constant compression load. It is seen that T-joint geometry has an effect on stress distributions obtained under buckling loads.

***Keywords:*** Composites, buckling, finite elements method, stress analysis

## 1. INTRODUCTION

Sandwich structures find their use in many applications namely in aerospace, automotive and marine structures. Sandwich composites are formed by bonding two thin faces to a thick core. The thin facings provide nearly all of the bending rigidity to the construction. The core transmits shear between the thin facings. The core also provides most of the shear rigidity of the sandwich construction. The core should possess good compression properties in order to prevent crushing of the core.

The assembly of composite structures in marine use necessitates the use of efficient joining methods. A common type of joint used in structural applications is the composite T-joint formed between the hull and the bulkhead [1]. It consists of composite overlaminates to form a large fillet, as shown in Fig. 1[2]. In marine applications, T-joints are used to transmit flexural, shear and tensile loads between the hull and the bulkhead, which are the primary structures in maintaining the ship stiffness under various loadings. These loads may be due to wave impact, structural and cargo weight, etc.[1]

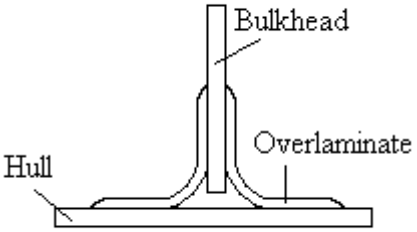



**Fig. 1:** T joint [1]

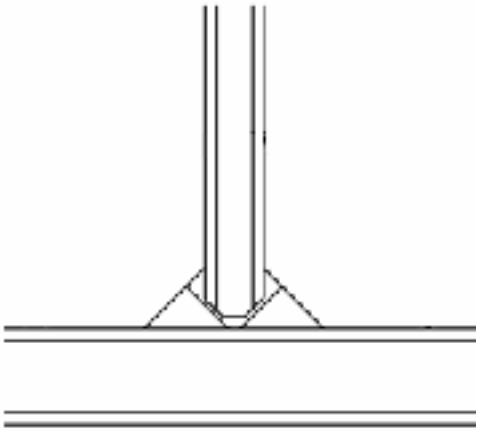


**Fig. 2:** DK-CND1 Type T –joint with two triangular foam fillets with no overlaminate.

Research on the structural behaviour of sandwich

structures has intensified recently [3, 4] due to their widespread usage in industry. [5–9]. The aim is to determine the effect of design parameters through combination of experiments and finite element analysis.

To ensure the T-joint reliability, the behaviour and performance under various loading conditions must be known. Hawkins and Shenoi [2] have investigated geometry effects, including fillet radius and overlaminate thickness in sandwich T-joints. Ferry Dharmawan et. al. [1] have investigated the effect of the geometry of the T-joint on the strain distribution using finite element analysis. Their results showed that the critical strains were significantly affected by the joint geometry.

Many authors such as Bazant and Cedolin [10] have carried out studies to investigate the buckling load in sandwich joints. They have derived a buckling formula for sandwich joints. The differences between the predictions of various buckling formulae [11] are explained by Bazant[12]. Haung and Kardomateas [13] presented a solution for the buckling behaviour of sandwich beams including transverse shear effects. Theoretical prediction of buckling loads for sandwich columns with metallic and laminated facings and foam core are studied by Kardomateas et. al. [14]. Buckling and failure analysis of FRP faced sandwich plates are studied by Muc and Zuchara [15]. A compression loaded sandwich column containing a debond is analyzed by Østergaard [16] using nonlinear finite element model. Heimbs et. al. have carried out experimental and numerical analysis of composite folded sandwich structures under compression[17] Attard et. al. have developed macro buckling equations for a sandwich column. The buckling formulation includes the axial deformation prior to buckling and the transverse shear deformation of core and face sheets [18].

In this paper, the effects of the T-joint geometry on buckling loads and stress distribution under uniform axial compression are investigated experimentally and numerically. Six types of T-joint geometries are considered, namely, continuous core in joint with right angle, core removed at joint, core with wedge fillet, core with 25 mm radius fillet, core with 70 mm radius fillet and DK-CND1 of Toftegaard and Lystrup with overlaminate (DK-CND1 type T –joint is one with two triangular foam fillets with no overlaminate and is shown in Fig. 2) [19,20]. The results show that the geometry of the T-joint area affects the buckling loads. T-joint geometry also has a strong effect on the critical stress.

## 2. EXPERIMENTAL AND NUMERICAL PROCEDURE

The aim of the experimental investigation is to validate the results of the FEM analysis for the T-joints under compression load. Experimental investigation for the determination of buckling load carrying capacity was carried out on sandwich T-joints, manufactured in six different geometries. The geometry and the dimensions of the T-joints considered in this study are shown in Fig. 3. The descriptions of each type of joint geometry are given in Table l.

Hand-lay up application, room temperature curing and simple abrasion of the surface with 120 grid paper were utilized to manufacture the T-joints. As shown in Fig. 3, a 25 mm thick sandwich bulkhead is joined at right angles to a 40 mm thick sandwich hull by means of 5 mm thick GRP skins and overlaminates. The sandwich composite consists of glass reinforced plastic GRP laminates made from chopped strand mat and orthophitalic polyester over a core of PVC foam (Divinycell H80). All joints have a width of 30 mm. The length of overlaminates for all joint types is given in Fig. 3. The dimensions given as 5 and 10 mm in Fig. 3 for types C, D, E and F indicate the thickness of the PVC foam material. This material is placed in between the hull and the bulkhead in order to withstand the probable compression stresses. The accuracy of the dimensions of the manufactured specimens was ensured by sanding and grinding them as shown in Figs. 4a and d. The method of attachment of the core pieces cut in 25° and 70° radii to the T-joint for types D and E is shown in Figs 4b and c[21].

The material properties were determined experimentally. Young's modulus, E and shear modulus, G, of the composite material were determined by

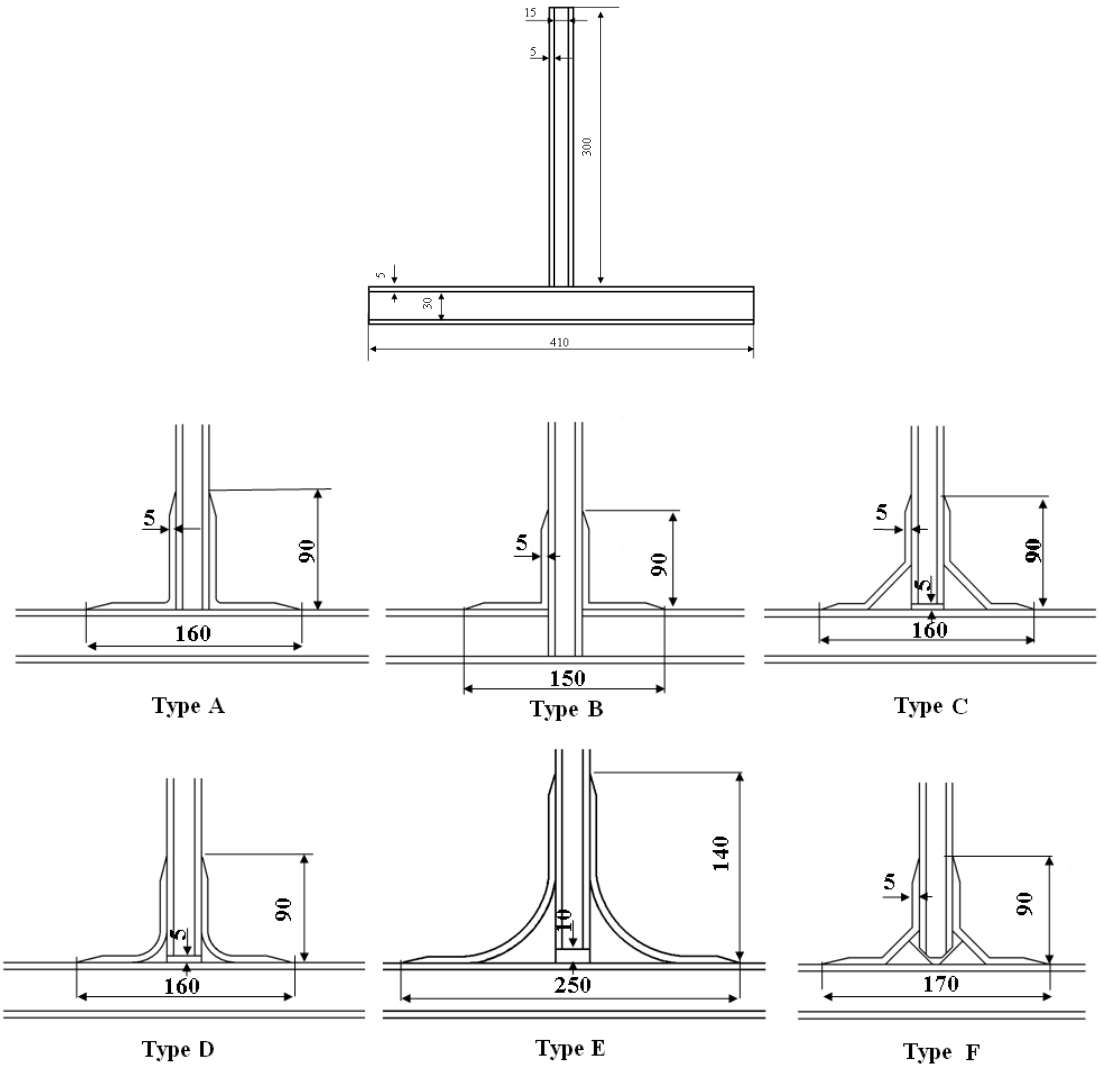



**Fig. 3:** a) Overall geometry and dimensions of the bulkhead and hull in T-joints, b) Geometry and dimension details of joint types

**Table1:** Descriptions of T-joint geometries

| Type A | Type B | Type C | Type D | Type E | Type F |
|---|---|---|---|---|---|
| continuous core in joint with right angle | core removed at joint | core with wedge fillet | core with 25 mm radius fillet | core with 70 mm radius fillet | DK-CND1 of Toftegaard and Lystrup with the overlaminate [19] |

means of tensile tests on bulk samples instrumented with an extensometer and strain gauges. Characteristic properties of the core and face material are given in Table 2.

Experiments were carried out on an Instron (model 1114) universal testing machine. The specimens were free to move at the top. The loading speed was 2 mm/min. Fig. 5 shows the testing arrangement and load application direction. Loads were applied gradually (250 N, 500 N, 750 N,….) until the failure was occurred. During the tests strains in critical points were measured by strain gauges. Measured strains and forces applied gradually were recorded.



(a)



(b)



(c)



(d)

**Fig. 4:** a) Manufacture procedure of the T-joint, sanding, b) Method of attachment of the core pieces cut in 25° radius, c) Method of attachment of the core pieces cut in 70° radius, d) Final grinding

**Table 2:** Material Properties

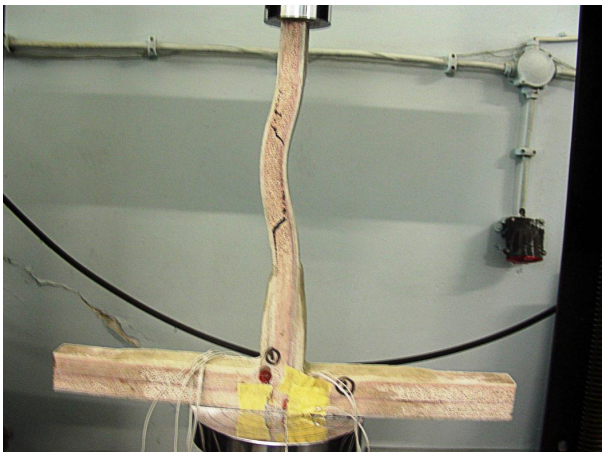
| **Property** | **Core material H80** | **Face material GRP** |
|---|---|---|
| Density(kg/m$^3$) | 80 | 1500 |
| Young□s Modulus (MPa) | $E_c$= 80 | $E_f$= 11000 |
| Shear Modulus (MPa) | $G_c$=29 | $G_f$= 4010 |

When the first buckling mode shape appeared, the load corresponding this was recorded as the critical buckling load.

Buckling load calculations in literature are given for straight sandwich columns. Therefore, the buckling load for a straight sandwich column with 300 mm length and 25 mm thickness (with 5 mm thick skins on each side of the core) is determined experimentally. The specimen was fixed at the bottom and was free to move at the top. When the first buckling mode shape appeared, the load corresponding this was recorded as the critical buckling load. Experimental and FEM results were compared with theo-




(a)



(b)

**Fig. 5:** a) Universal test machine b)Testing arrangement

retical ones in order to validate the accuracy of the FEM results.

Linear (eigenvalue) buckling analysis was conducted using the commercial code ANSYS. GRP and the foam were assumed as linear elastic materials. Joints were modelled in two dimensions and meshed using four node quadrilateral elements (PLANE42). The dimensions indicated in Fig. 3 were employed for FEM. As an example, FEM model for type A T-joint, which consists of 12377 elements and 12790 nodes, is shown in Fig. 6.

## 3. RESULTS

### 3.1 Experimental Results

A sandwich composite loaded in compression can fail in various ways. The following local buckling modes (also called failure modes) can be identified [22]:

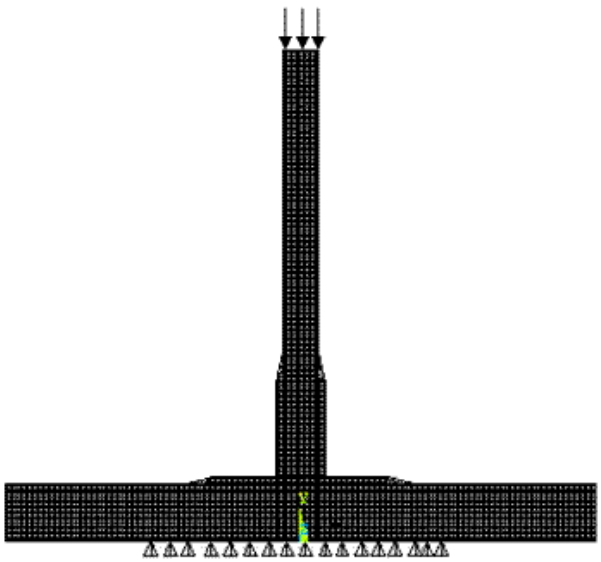


**Fig. 6:** FE model of "A type" T-joint

In wrinkling of face sheets, the skin may buckle inwards or outwards, depending on the flatwise compression strength of the core [23]. The second form is dimpling of face sheets, in which skins may buckle or dimple into the spaces between core walls to form wrinkles and the third form is shear crimpling, which is a general form of buckling. It causes the core fail in shear at the crimp and the skins remain undamaged; it may also cause shear failure in the bond between the facing and the core.

The load carrying capability of the sandwich T-joints are influenced from local buckling. Experimental results show that joints tested under compression have similar failure modes. The predominant failure mode is observed to be shear failure of the core. Fig. 7 shows failure that occurred in the bulkhead region on Types D, B and A joints.

The crack initiated at the interface between the skin and the foam and by propagating inside the foam, it

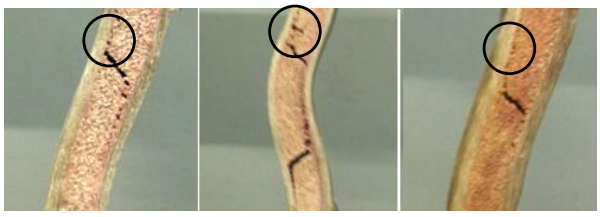


**Fig. 7:** Failure of T-joints under buckling (examples are given for Type D, B and A T-joints), circles indicate crack initiation sites.

reaches to the interface at the other side of the bulkhead. Final failure occurs as shown in Fig. 7.

### 3.2 Numerical Results

Firstly, in order to prove the accuracy of the FEM model of the T joints for the calculation of the buckling load, a straight sandwich column is considered and critical buckling loads are computed as follows:

According to Bazant and Cedolin [10], the critical buckling load is calculated as:

$$P_{cr} = (EI)_{\alpha} k_{cr}^2 \Big/ \left[ 1 + \frac{k_{cr}^2 (EI)_b}{GA_1} \right] \quad (1)$$

where,
$k_{cr}= \pi/(2L)$ for cantilever columns,
$(EI)_{\alpha}=E_f'(I_1+I_f)$
$(EI)_b=E_f'I_1$, where
$E_f'=E_f/(1-\upsilon_f^2)$
$I_1=(h/2)(c+h)^2B$ , $I_f=(h^3/12)B$ and
$\upsilon_f^2= \upsilon_{12}\, \upsilon_{21}$ for composite facings,
$GA_1=G_c(h+c)B$

A column of width B, face thickness h, core thickness c and column length L is considered.

Table 3 presents the results of the buckling loads computed by the Bazant and Cedolin Formula, FEM analysis with that obtained experimentally. This way, it has been verified that FEM results yield compatible values compared to experimental results and Bazant and Cedolin formula, as seen in Table 3.

Secondly, after the verification of the suitability of the FEM analysis in the prediction of critical buckling loads for sandwich joints, FEM analysis has been carried out for T-joints. Results obtained from experiments and FEM analyses are summarized in Fig. 8. For comparison, the buckling load of a straight column is included in the figure. FEM analysis results may yield higher values compared to experimental results since imperfections and nonlinearities may prevent most real-world structures from achieving their theoretical elastic buckling strength.

It is seen from Fig. 8 that buckling loads are influenced by the T-joint geometry. Both experimental and numerical results show that Type E is the best geometry for the buckling loading. Due to a large fillet radius, the buckling length decreases and the moment of inertia increases, which, in turn, increase the critical load. Small fillet radius acts as sudden geometry change in Type D, which causes the occurrence of a small critical load in this type of joint. Compression stress distribution obtained from FEM analysis of the T-joints under critical buckling loads are shown in Fig. 9 for two joint types, namely Type D and Type E, which give the lowest and the highest stresses along the bulkhead, respectively. Maximum compression stresses for all joint types under respective critical buckling loads are summarized graphically in Fig. 10a. Similar to Fig. 8 which shows the critical buckling loads, the maximum compression stresses are highest for Type E and lowest for Type D. Fig. 10b shows the maximum compression stresses for joint types D and E under F=2000N load. It is seen that T-joint geometry does not have a significant effect on the stress under the constant compression load.

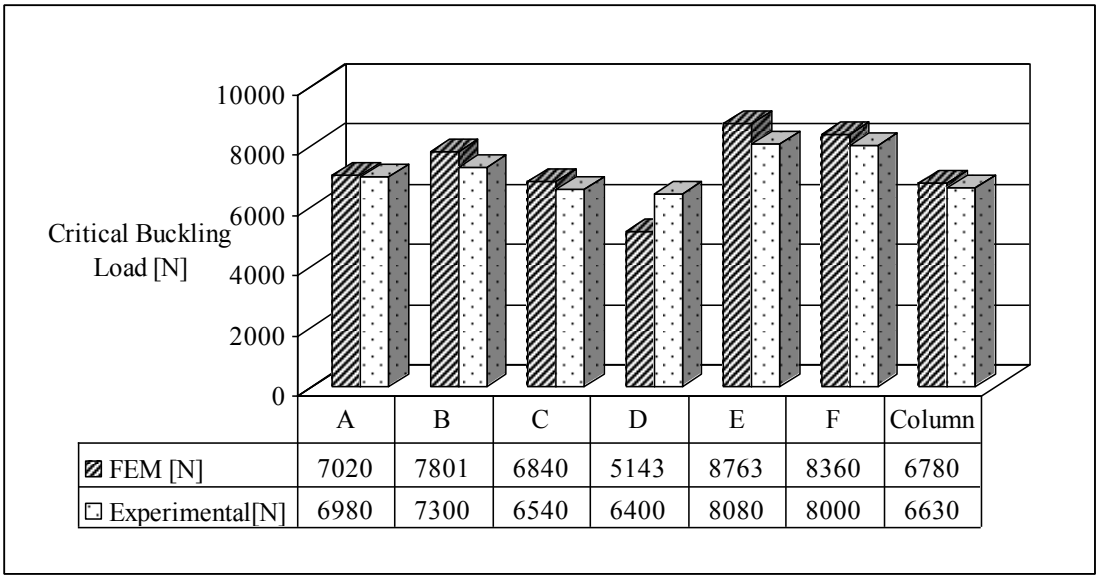
## 4. CONCLUSIONS

This paper deals with the experimental and numerical analysis of sandwich T-joints in terms of buckling loads, which are used in marine applications. The GRP/PVC sandwich composite T- joints have been manufactured in six different geometries.

The load carrying capability of the sandwich T-joints are influenced from local buckling. Experimental results show that joints tested under compression have similar failure modes, which is core shear. Core shear can be overcome by selecting a core material

**Table 3:** Buckling load values for sandwich columns (in Newtons).

| Bazant and Cedolin Formula | FEM | Experimental |
|---|---|---|
| 6632 | 6780 | 6630 |




| | A | B | C | D | E | F | Column |
|---|---|---|---|---|---|---|---|
| FEM [N] | 7020 | 7801 | 6840 | 5143 | 8763 | 8360 | 6780 |
| Experimental[N] | 6980 | 7300 | 6540 | 6400 | 8080 | 8000 | 6630 |

**Fig. 8:** Buckling loads for T-joints obtained by FEM analysis and experiments.

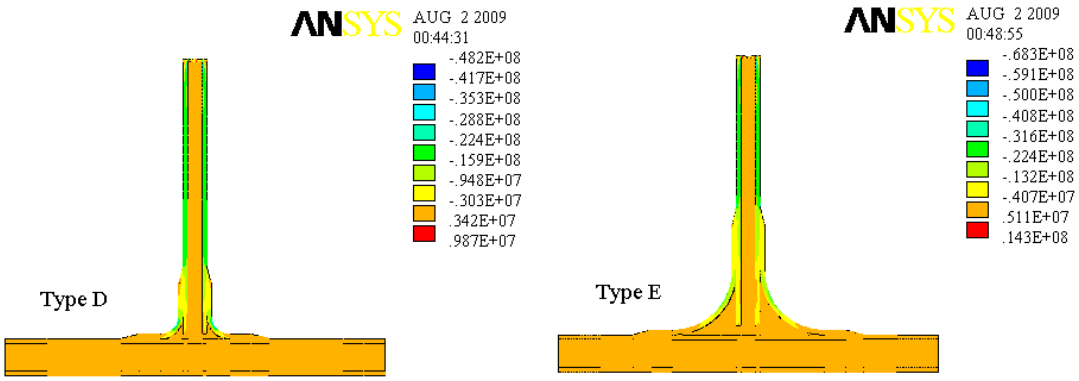
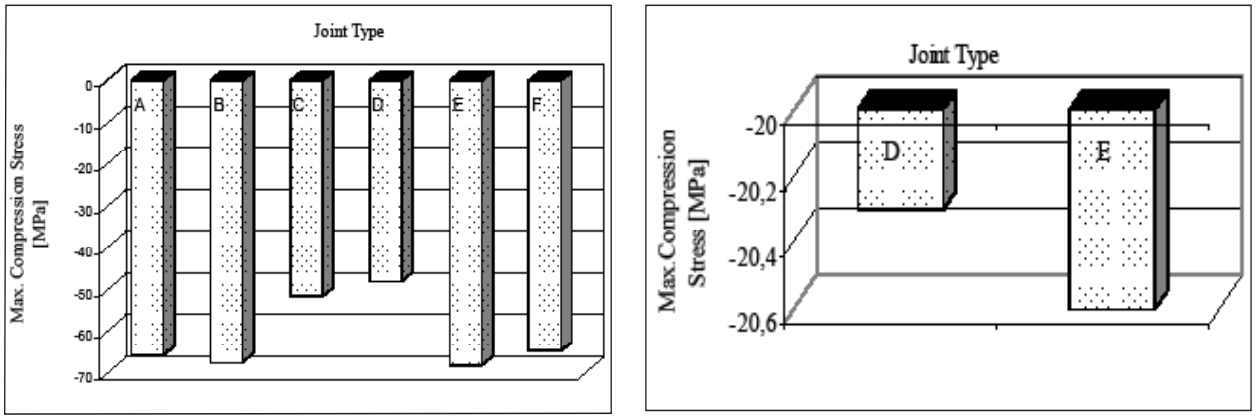



**Fig. 9:** Maximum compression stress distribution for Type D and Type E joints under Critical Buckling Loads




(a) (b)

**Fig. 10:** a) Maximum compression stresses obtained from FEM analysis for each type of joint under Critical Buckling Load ,b) Maximum compression stresses obtained from FEM analysis for D and E types of joints under F=2000N

with better mechanical properties, which can carry the general shear forces more adequately.

It has been verified that FEM results yield compatible values compared to experimental results. Therefore, the suitability of the two-dimensional finite element model for the study of sandwich T-joints is confirmed. Numerical results reveal that T-joint geometry has a strong effect on the critical loads obtained by buckling. Stress distributions in T-joints have also been investigated under critical buckling loads and for a constant compression load. Examination of stress reveals that the joint subjected to the highest critical buckling load will have the greatest constraint, thereby the highest stress.

Both experimental and numerical results show that Type E, core with 70 mm fillet radius, is the best geometry in terms of the buckling loads. It is suggested that Type E joint is much more suitable to work such as deck loads in boats.

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