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NUMERICAL AND EMPIRICAL INVESTIGATION OF BOLTED SANDWICH JOINTS WITH LAMINATE SKINS

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Abstract- For the optimization of load-carrying capacity of bolted connections, several formulas of the stiffness of bolted members have been proposed for homogenous and isotropic materials contrary to composite sandwich ones whose integration in bolted structures is still insufficiently treated. In this paper, an empirical formula is proposed for the equivalent modulus of sandwich joints members considered as a primordial parameter that expresses the global stiffness, so, a finite element model is proposed, validated according to literature findings and adopted to simulate many designs of preloaded sandwich bolted joints with carbon and glass laminated skins, then, a search algorithm is performed in order to investigate numerical results and determine a global expression of the equivalent member modulus that depends on the characteristics of core and skins materials. Further, a parametric analysis of the variation of stiffness in terms of joints characteristics demonstrate that the impact of sandwich facings which hold the main Von Mises stresses is extremely interesting comparing to core, also, in the case of important bolt diameters and skins materials with an elastic modulus less than 121 GPA studied stiffness is higher; besides this, when bolt preload rises considerably, maximum principal stress is reduced at the expense of maximum shear which improves the risk of core failure.

Keywords: Sandwich Bolted Joint, Member Stiffness, Equivalent Member Modulus, Bolt Preload, Parametric Study.

1. INTRODUCTION

Composite and sandwich materials are integrated in several industrial systems [1-2] and used in a wide range of competitive domains (automotive [3], aeronautic [4] …) because of the variety of their fabrication techniques that aim to diversify their mechanical characteristics [5] according to operating conditions [6]. Most of researches that treated the behavior of bolted sandwich parts considered experimental and numerical investigations of equivalent stresses, failure modes and load carrying capacity. Thus, concerning flexural response, Zhu, et al. [7] investigated performances of a bolted splice joint between two lattice core sandwich panels, also Satasivam et al. [8] studied a bolted sandwich structure with composite components in the form of I or box profiles sections placed between two plates, they showed a drop of bending stiffness for increasing flexion force and noted two principal failure modes, a web-core buckling due to shear stresses and upper skin failure due to in-plane compression. The prediction of failure load and the analysis of damage progression process in the presence of bolts [9] are primordial to detect vulnerable zones in a sandwich joint and optimize its geometric specifications [10].

Regarding to the modest number of studies about bolted sandwich components with laminate skins and foam cores, the analysis of performances of some connection solutions adopted for joints containing laminate composite members can be extremely useful [11]. For the sake of strengthening a fastened assembly, the insertion of bolts requires a clamping force whose influence on stiffness and on failure response of connected parts was treated in several papers [12].

The calculation of member stiffness is strongly required in order to obtain a reliable bolted joint design. For that, approximated functions have been used to model the in-plane compression stresses in a bolted assembly; these constraints are distributed mostly as a conical envelope along bolt shank direction. Nassar et al. [13] used a fourth order polynomial to express pressure under bolt head and performed numerical and experimental tests of an aluminum joint to verify the suggested model, similarly, a third order polynomial was used for the representation of bolt pressure [14], it showed a better numerical accuracy than the fourth order one [13]. Canyurt, et al. [15] pursued an alternative approach based on a genetic algorithm to find a non-linear and non-dimensional formula of stiffness validated according to [16].

In this paper, a 3D Finite Element Model realized under ANSYS software is elaborated to simulate a series of bolted sandwich joints under bolt preload, then, numerical results are analyzed through a search algorithm to express an analytical approximation of the equivalent modulus of each joint member.

This modulus is adopted for stiffness calculation. Besides this, the variation of the values of stiffness in terms of joints specifications and applied preloads is analyzed to study the impact of the properties of tested samples on mechanical strength, stresses distribution and probable failure modes.

2. NUMERICAL SIMULATION

2.1. Test Specimens

Simulated joints are composed from two identical sandwich parts having variable heights and fixed length (70 mm) and width (48 mm). Two core thicknesses (8 and 14 mm) are used with several skins' heights varying from 1 to 4 mm. Bolt dimensions [17] are selected according to the standard ISO 4014 for many diameter values included between 14 and 20 mm. Dimensional specifications of test specimens are presented in Table 1. Figure 1 shows principal constituents of studied structures [18].

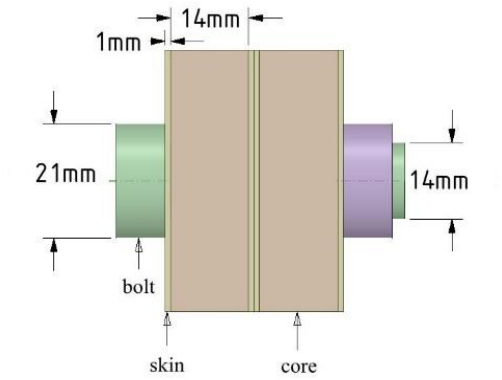

Figure 1. An example of studied joints (sample 12) [18]

Table 1. Geometry specifications of test specimens

No.	Bolt diameter (mm)	Skin thickness (mm)	No.	Bolt diameter (mm)	Skin thickness (mm)
Core thickness=8 mm			Core thickness=14 mm		
1	14	1	12	14	1
2	14	2	13	14	2
3	16	1	14	16	1
4	16	2	15	16	2
5	16	3	16	16	3
6	16	4	17	16	4
7	18	1	18	18	1
8	18	1.5	19	18	1.5
9	18	3	20	18	3
10	20	1	21	20	1
11	20	2	22	20	2

The study is held for standard steel bolt joining two sandwich members with SAN or PVC foam core attached to two woven laminate skins made from four layers of carbon (C1, C2, CR1 and CR2) or glass (G1 and G2) material with four orientations (0°/45°/-45°/90°). Materials properties are shown in Tables 2, 3 and 4 [18].

Table 2. Properties of bolt material [18]

Structural steel	
$\delta_{Leh}=\dfrac{2F_i \ln\left[\dfrac{\left(2\tan(\alpha)l+D-d\right)\left(D+d\right)}{\left(2\tan(\alpha)l+D+d\right)\left(D-d\right)}\right]}{\pi Ed\tan(\alpha)}$ $(\alpha=30°)$ (Kg.m^{-3})	7850
E (MPa)	200000
$\delta_{Nass}=\dfrac{2\ln\left[\dfrac{\left(2\tan(\alpha)l+D-d\right)\left(D+3d\right)}{\left(2\tan(\alpha)l+D+3d\right)\left(D-d\right)}\right]}{\pi Ed\tan(\alpha)}F_i$ $(\alpha=30°)$ (MPa)	250
σ_t (MPa)	460
v	0.3

Table 3. Properties of skins materials [18]

Property	Woven carbon laminates				Woven glass laminates	
	C1	C2	CR1	CR2	G1	G2
ρ (Kg.m^{-3})	1480	1420	1490	1540	2000	2000
E_x and E_y (MPa)	91820	61340	121000	209000	50000	45000
E_z (MPa)	9000	6900	8600	9450	8000	10000
v_{xy}	0.05	0.04	0.27	0.27	0.3	0.3
v_{xz} and v_{yz}	0.3	0.3	0.4	0.4	0.4	0.4
G_{xy} (MPa)	19500	19500	4700	5500	5000	5000
G_{xz} and G_{yz} (MPa)	3000	2700	3100	3900	3846.2	3846.2

Table 4. Properties of core materials [18]

Core material	PVC Foam	SAN Foam
ρ (Kgm^{-3})	80	81
E_x and E_y (MPa)	102	60
E_z (MPa)	102	60
v_{xy}	0.3	0.3
v_{xz} and v_{yz}	0.3	0.3
G_{xy} (MPa)	39.231	23.077
G_{xz} and G_{yz} (MPa)	39.231	23.077

2.2. Finite Element Model

Studied sandwich joints are subjected to the preload magnitude F_i ; their numerical investigation is carried out under the commercial software ANSYS through the adoption of a 3D Finite Element Model obtained from combining the simulation of sandwich members under ACP PRE and the representation of bolt under MECHANICAL MODEL. As a boundary condition, top surface of the head of the preloaded bolt is fixed (Figure 2 [18]).

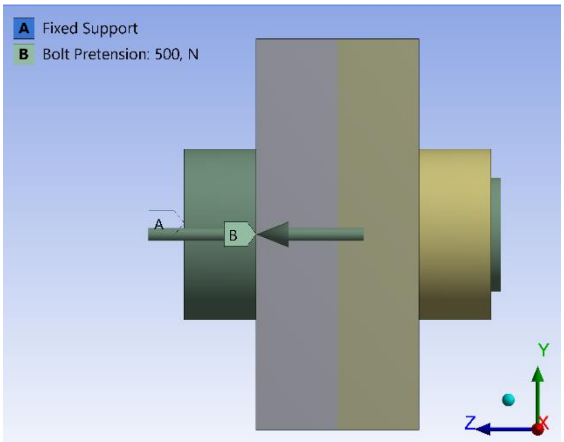

Figure 2. The applied boundary condition with 500 N of preload [18]

An adaptive meshing with an automatic generation of mesh size and order is considered for the two simulation concepts used in the performed analysis. Consequently, the mesh element SOLID 185 defined by eight nodes and recommended for orthotropic materials is adopted for joint members, SOLID 187 with 10 nodes is used for screw and SOLID 186 with 20 nodes for nut, important elements orders are selected for bolt because of its role in carrying applied preloading, small values of aspect ratio implying compact elements shapes are recorded for the bolt and for the holed region of joint members considered as a critical zone that requires high mesh quality. Besides these parameters, main types of mesh that characterize simulated specimens are tetrahedron used for screw and hexagonal adopted for the rest of the modeled structure (Figure 3) [18].

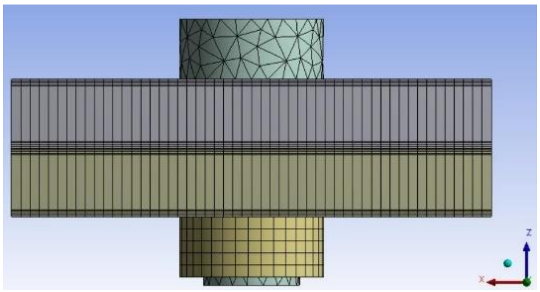

Figure 3. FEM mesh [18]

Knowing that treated displacements in this study are resulted from bolt preload, they are recorded along the *z*-axis and not along transverse directions; so, a frictionless contact is selected between fastened members instead of a frictional one to reduce calculation time. On the other hand, the consideration of thread necessitates specified tests to determine friction coefficient between sandwich parts and the bolt, for that, the conducted simulation supposes a null relative displacement between lateral surface of the bolt and the joint and considers a bonded contact between them; the other contact areas between bolt and joint are also bonded.

According to the augmented Lagrangian algorithm, conditions of contacts between the components of each modeled joint are considered as constraints imposed to the equations of motion solved by ANSYS software; in fact, contact forces are included in the expression of the applied reaction force and several iterations are executed so that the resulting penetration is smaller than an allowable tolerance. The adoption of the Lagrangian method guarantees a flexible solution to the contacts problems existing in the modeled structures.

2.3. Validation of Finite Element Model

For the purpose of validating the proposed FEM model, conditions clarified in the previous section are used to elaborate a numerical simulation of an aluminum joint (Table 5 [18]) that has the same geometric specifications as sample 1 defined in Table 1.

Table 5. Properties of the aluminum alloy constituting tested aluminum joint [18]

Aluminum alloy	
ρ (Kg.m^{-3})	2770
E (MPa)	71000
σ_y (MPa)	280
σ_t (MPa)	310
ν	0.3

FEM deformations resulted from the application of bolt preload are compared to the ones deduced from three principal formulas of member stiffness (Table 6) approved in literature [13-19 and 20] where each adopted analytical reasoning is proved either by numerical [19] or by experimental results [20].

Table 6. Equations of member deformation in literature [13-20]

Researcher	Deformation formula	
Lehnhoff	$\delta_{Leh}=\dfrac{2F_i\ln\left[\dfrac{(2\tan(\alpha)l+D-d)(D+d)}{(2\tan(\alpha)l+D+d)(D-d)}\right]}{\pi Ed\tan(\alpha)}$ $(\alpha=30°)$	(1) [19]
Wileman	$\delta_{Wil}=\dfrac{F_i}{EdG\exp\left(F\dfrac{d}{2l}\right)}$ $(G=0.7967; F=0.63816)$	(2) [20]
Nassar	$\delta_{Nass}=\dfrac{2\ln\left[\dfrac{(2\tan(\alpha)l+D-d)(D+3d)}{(2\tan(\alpha)l+D+3d)(D-d)}\right]}{\pi Ed\tan(\alpha)}F_i$ $(\alpha=30°)$	(3) [13]

where, E is young's modulus of joint members. F_i is the magnitude of bolt preload, d and D are diameters of the bolt and the bolt head, respectively. l is member thickness.

Figure 4 [18] clarifies that FEM results converge to analytical ones presented in Table 6 [13-20] with a maximum percent error of 0.52% for the Equation (1), 4.87% and 14.07% for Equations 2 and 3, respectively.

Stiffness expressions introduced by Equations (1) and (2) are more adapted to collected numerical data. According to the accomplished verification, conditions and hypotheses used to define the proposed FEM model are validated.

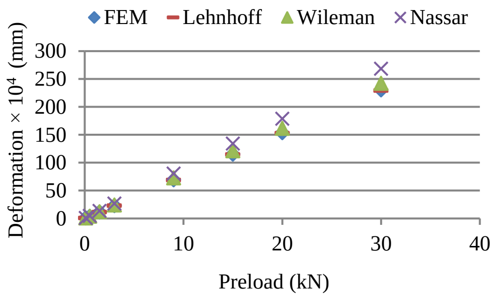

Figure 4. Results of the deformation of aluminum member [18]

3. EQUIVALENT MEMBER MODULUS

Member stiffness K influences the transfer of loads, determines joint strength and characterizes its capacity to carry the applied loading without achieving yield mode. For that, the prediction of how member materiel affects K is strongly recommended. So, in this paper, for each preload, numerical results of stiffness Equation (4) [19] are investigated and an empirical analysis of collected FEM data is performed to deduce an analytical formulation of the equivalent member modulus E_{eq} (Equation (7)).

$$K = F_i / \delta_i \tag{4}$$

where, δ_i is the FEM displacement of the sandwich member along z-axis caused by preload, and δ_i is measured at hole zone and expressed according to [19].

$$\delta_i = \int_0^{l_s} \frac{dz}{S(D,d,z)} \frac{F_i}{E_{eq}} \tag{5}$$

$$K = \frac{F_i}{\delta_i} = E_{eq} \frac{1}{\int_0^{l_s} \frac{dz}{S(D,d,z)}} \tag{6}$$

$$K / E_{eq} = f(D, d, l_s) \tag{7}$$

where, l_s is sandwich member thickness, and S represents the corresponding pressure area at each position in z-axis. According to the standard ISO 4014, the diameter of the bolt head D is equal to $1.5d$. So, Equation (7) can be rewritten as:

$$\frac{K}{E_{eq}} = f(d, l_s) \tag{7}$$

In order to simplify the empirical analysis, an analytical formulation is proposed for the equivalent strain produced by preload which is considered as a linear combination of the axial strain related to the average of core and skins elastic moduli along z-axis plus the strain generated by the contribution of skins modulus along x-axis. So, a triplet noted $(\alpha, \varphi, \gamma)$ supposed less than (1, 1, 1) permits to determine E_{eq} [21].

$$\varepsilon_{eq} = \frac{\sigma_{eq}}{E_{eq}} = \sigma_{eq}\left(\frac{\alpha}{\alpha_{skins}E_{z_{skins}} + \alpha_{core}E_{z_{core}}} + \frac{\varphi}{\gamma E_{x_{skins}}}\right) \tag{8}$$

$$E_{eq} = \frac{1}{\dfrac{\alpha}{\alpha_{skins}E_{z_{skins}} + \alpha_{core}E_{z_{core}}} + \dfrac{\varphi}{\gamma E_{x_{skins}}}} \tag{9}$$

The triplet used to express the equivalent member modulus according to the Equation (9) is determined in terms of properties of tested samples in the form of proportions characterizing their dimensions or their material type like the volume fractions of their constituents or poisson's ratios.

For each bolt diameter and member's thickness, K / E_{eq} is supposed constant according to Equation (7), for that it is represented by a constant A_{d,l_s}. Thus, in order to deduce the analytical representation of the equivalent member modulus from numerical results, an empirical approach is adopted by using the Microsoft Office Excel solver tool; its principal steps are detailed in Figure 5.

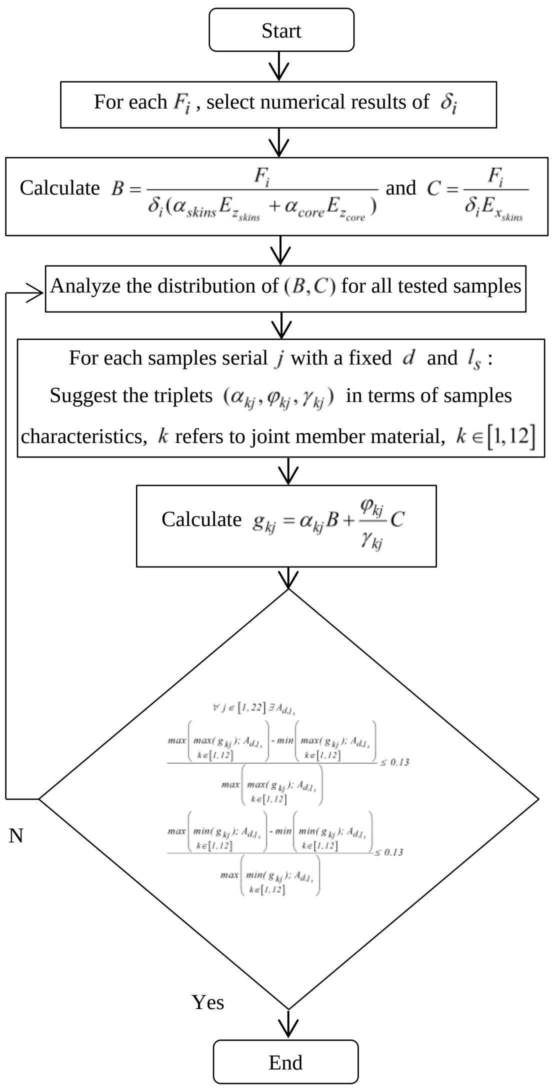

Figure 5. Flowchart of the algorithm used to find the equivalent member modulus [22]

4. RESULTS AND DISCUSSIONS

As a consequence of the application of three different preloads (0.06, 0.5 and 30 kN), the developed stress spreads from the bolt and occupies a specific region that depends on geometric and material properties of studied joints. The maximum von Mises stress occurs at the top skin around bolt hole (Figure 6 [18]), also no considerable constraints are remarked far from bolt region which justifies the choice of measuring the displacement δ_i (Figure 7 [18]) in hole zone. δ_i is collected for each simulated joint specimen and K is calculated according to Equation (4).

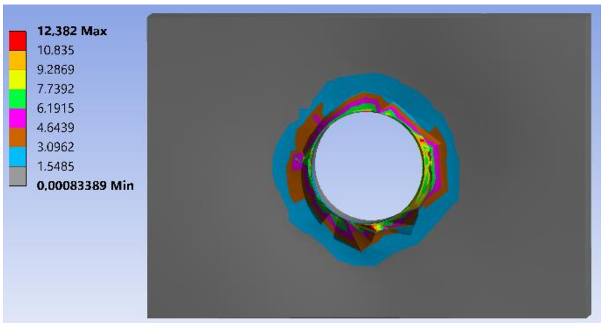

Figure 6. Von Mises stresses for sample 19, C1 skins, PVC core and 500N of preload [18]

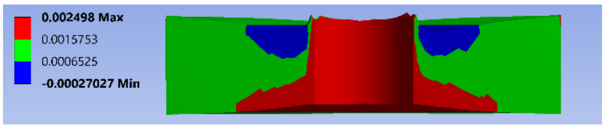

Figure 7. Member displacement along z-axis for sample 19, C1 skins, PVC core and 500N of preload [18]

4.1. Equivalent Member Modulus

For tested joints, the performed algorithm confirms that replacing $(\alpha_{kj}, \varphi_{kj}, \gamma_{kj})$ by $(\alpha_{skins}, \alpha_{core}, \nu_{xz})$ solves the treated problem. So, K / E_{eq} is approximately constant for varied sandwich materials, fixed preload, bolt diameter and member thickness, it is represented by the constant A_{d,l_s} whose found values are specified in Table 7 [18]. The definition of A_{d,l_s} introduces a theoretical stiffness K_{ap} expressed according to Equation (10).

$$K_{ap} = A_{d,l_s} E_{eq} \tag{10}$$

Theoretical stiffness converges to numerical one with a maximum percent error of 12.9% for 0.06 and 0.5 kN of preloads applied to the joint sample 2 with PVC foam core and CR2 skins. The formula of E_{eq} (Equation (9)) becomes:

$$E_{eq} = \frac{1}{\dfrac{\alpha_{skins}}{\alpha_{skins} E_{z_{skins}} + \alpha_{core} E_{z_{core}}} + \dfrac{\alpha_{core}}{\nu_{xz} E_{x_{skins}}}} \tag{11}$$

Similarly, to [23] that emphasized the effect of the material of two composite beams connected to a steel column on rotational stiffness, the determination of the equivalent member modulus characterizes sandwich joint resistance.

Table 7. The distribution of $A_{d,l_s} \times 1000$ in terms of joints Specifications [18]

Bolt diameter (mm)	Skin thickness (mm)	Core thickness (mm)	Preload (kN)		
			0.06	0.5	30
14	1	14	21.761	22.251	26.155
14	2	14	27.615	27.615	31.499
16	1	14	23.326	23.326	27.615
16	2	14	33.918	34.401	36.91
16	3	14	37.777	37.874	39.605
16	4	14	37.296	37.296	38.259
18	1	14	25.668	26.058	31.208
18	1.5	14	28.199	27.615	32.758
18	3	14	37.296	37.296	41.43
20	1	14	28.101	28.101	32.467
20	2	14	34.981	35.271	38.932
14	1	8	21.761	22.153	25.668
14	2	8	32.177	32.177	37.777
16	1	8	22.544	22.544	27.421
16	2	8	31.789	32.08	36.332
16	3	8	35.367	35.946	38.932
16	4	8	39.221	37.488	39.221
18	1	8	26.155	27.129	31.499
18	1.5	8	30.529	30.723	35.174
18	3	8	39.221	40.182	43.059
20	1	8	23.717	23.326	28.587
20	2	8	35.85	36.139	39.221

4.2. Parametric Analysis of Member Stiffness

4.2.1. The Influence of Preload on Member Stiffness

FEM results show that when bolt preload increases from 0.06 kN to 0.5 kN member stiffness still approximately constant with a maximum error of 0.08%, although the application of higher preload (30 kN) exhibits a sandwich stiffness increase for all studied samples. Numerical results confirm that for an important preloading, the ratio of maximum shear on maximum principal stress increases remarkably in the circumference of bolt hole at the interface between the bolt head and the joint, so shear constraints grow up at the expense of compression ones, consequently, studied stiffness that depends on axial deformation rises, nevertheless, the risk of member failure by core shear is enhanced around bolt hole.

In the case of joints with carbon skins, the lowest augmentation of stiffness with preload is recorded for members with the stiff laminates CR1 and CR2 and the highest equivalent modulus, then comes members with C1 and C2 that have the lowest modulus and the biggest growth of K that achieves 21.3% for SAN foam core, 16 mm of bolt diameter, 1 and 8 mm of skins and core thicknesses, respectively. Concerning glass laminated skins, when the relative difference between the values of K increment introduced by G1 and G2 is higher than 2%, parts with G2 face sheets having the biggest equivalent modulus show the smallest K growth. Generally, the most important improve of stiffness with preload is obtained for lower E_{eq} allowing noticeable evolution of shear.

Besides this, Figure 8 [18] represents optimum values of stiffness rise with preload for each face sheets material, it shows that the relative gap between minimum and maximum growth of stiffness is greater for CR1 and

CR2 because of their considerable properties which influences strongly K when samples specifications change. Therefore, skins characteristics have an essential impact on the variation of member stiffness with the applied preload.

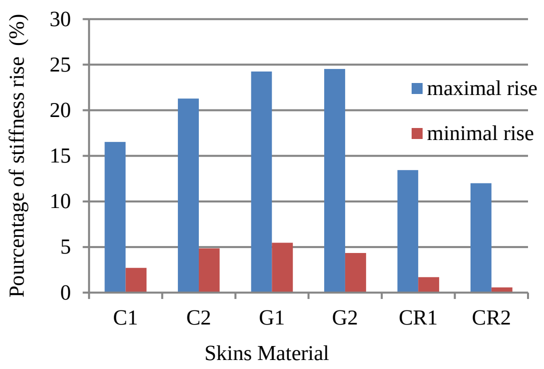

Figure 8. Optimum values of the stiffness rise resulted from preload enhancing [18]

4.2.2. The Influence of Bolt Diameter on Member Stiffness

FEM results clarify that the evolution of K according to bolt diameter keeps a similar trend for both PVC and SAN foam core. Thus, only the stiffness of sandwich members with PVC core is treated in this part and represented in Table 8 [18] for 30 kN of preload, 14, 16 and 20 mm of bolt diameters.

Table 8. Variation of member stiffness (kN/mm) according to bolt diameter [18]

Skins materiel	Core thickness (mm)	Skin thickness (mm)	Preload (30 kN)		
			d (mm)		
			14	16	20
C1	14	1	186.07	198.33	222.54
C2	14	1	151.52	162.67	179.89
G1	14	1	172.05	186.69	222.42
G2	14	1	180.82	196.09	219.59
CR1	14	1	199.51	211.6	237.27
CR2	14	1	241.55	249.07	284.85
C1	14	2	221.86	261.73	275.94
C2	14	2	183.16	212.19	226.43
G1	14	2	212.63	240.29	261.48
G2	14	2	220.91	250.21	273.12
CR1	14	2	239.16	285.74	297.03
CR2	14	2	285.93	353.74	355.39
C1	8	1	186.82	192.68	198.65
C2	8	1	154.51	160.17	165.97
G1	8	1	177.61	186.54	195.84
G2	8	1	190.13	199.65	210.13
CR1	8	1	198.23	202.96	208.32
CR2	8	1	240.23	242.19	245.12
C1	8	2	254.89	260.78	284.31
C2	8	2	211.24	216	232.72
G1	8	2	243.07	252.87	270.25
G2	8	2	251.85	263.53	285.52
CR1	8	2	273.03	277.67	304.01
CR2	8	2	341.54	331.06	368.39

In comparison with the research [15] that has approved through genetic algorithm methods and Yildrim [16] experimental results that the stiffness K increases highly with bolt diameter for a $d/2l$ ratio varying between 0.1 and 0.6; performed FEM results illustrate that when bolt diameter changes from 14 to 16 mm, all studied sandwich joints with a core thickness of 14 mm and an aspect ratio $d/2l$ varying from 0.39 to 0.5 show a member stiffness growth with the exception of the joint that is subjected to moderate preloads and has CR2 skins with 1 mm of height, its K decreases by 0.2%; this drop caused principally by limitations of software performances can be neglected, additionally, when core height is equal to 8 mm, $d/2l$ ratio is included between 0.58 and 0.8 and tested samples keep the same stiffness variation as ones with 14 mm of core thickness except some specimens with carbon rigid skins; their stiffness has a slight drop by a maximum rate of 6.6% for CR2 and 1.4% for CR1. The passage to a bigger bolt diameter that is equal to 20 mm induces an increase in most stiffness results with the exception of the one detected for the joint with thick CR2 skins (2 mm) and a core having 14 mm of thickness; K in this case decreases by about 2.45% at 0.5 kN of preload.

Consequently, the stiffness K increases approximately with studied bolt diameters varying from 14 to 20 mm, this increment is explained by the expansion of the contact area under bolt head which leads to the enlargement of the envelope of resulted pressure and the decrease of compression stresses. Nevertheless, in the case of stiff skins with high elastic modulus, stresses evolution for a growing bolt diameter exhibits some irregularities which affects the stiffness rise because of the concentrations of constraints created around bolt hole at the contact surface between the bolt head and the sandwich joint, concentrated stresses are caused by the geometric singularities introduced by the bolt hole that goes through sandwich face sheets containing fibers with high rigidity.

4.2.3. The Influence of Skins Material on Member Stiffness

Similarly, to [23] that has approved the rotational stiffness growth with increasing reinforcements ratio for a joint with two composite beams connected symmetrically to a steel column; performed numerical tests approve that for fixed preload, geometric specifications and core characteristics most specimens show a growing stiffness with the equivalent member modulus which is influenced highly by properties of face sheets material. Sandwich members could be classified from the least to the stiffest according to their skins as: C2-G1-G2-C1-CR1-CR2. On the other hand, in the case of some tested samples with G1, G2 and C1 facings, the mentioned classification is slightly disturbed by a maximum error of 5.6% for 30 kN of preload, a bolt diameter equal to 20 mm, 1 mm of skins and 8 mm of SAN foam core. Moreover, through changing face sheets material from C2 to CR2, analyzed joints approve a maximum increment of K by 45.8% for 0.06 and 0.5 kN of preloads and 40.2% for 30 kN. When the rigid carbon skins showing a small difference in E_z and high change of E_x are adopted and CR1 is replaced by CR2, the stiffness increase is remarkably important contrary to glass face sheets that have a significant variation of E_z and a small change of E_x, so, the evolution of sandwich member stiffness is more impacted by E_x than E_z because of the importance of plane mechanical characteristics of laminated skins.

4.2.4. The Influence of Skins Thickness on Member Stiffness

The growth of face sheets thickness for fixed specifications of core and bolt gives to joined members an increasing ability to resist preloading effect which implies a decrease in compression stresses and improves stiffness.

4.2.5. The Influence of Core Material on Member Stiffness

The change of core material from SAN to PVC foam that has the biggest elastic modulus implies a stiffness increase, so, for moderate preloads (0.06 and 0.5 kN), studied joints record 3.9% as a maximum rise of K with the exception of the sample N° 21 that shows for G1 skins an increase of K by almost 11.7%, on the other hand, at high preload (30 kN) maximum stiffness enhance is about 2.8% for most tested joints and 9.6% for the case evocated previously, Figure 9 [18] illustrates stiffness distribution for specimens having the same geometrical characteristics as the sample N° 21, varied skins materials and 30 kN of preload.

The highest increase of K with core elastic modulus is recorded for a great bolt diameter, thick core, moderate preload and thin G1 skins, all these parameters strengthen the role of the sandwich core in holding resulted stresses. When bolt preload grows up and achieves 30 kN, an advantageous rise of K happens for specimens with SAN foam core comparing to those with PVC, so stiffness differences due to core type are minimized at big preloading and percentages of the growth of K with core elastic modulus drop. Otherwise, regarding to the considerable enhance of the elastic modulus during the passage from SAN to PVC foam, the impact of core material on stiffness variation is still modest.

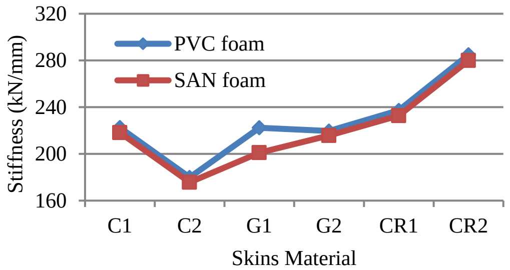

Figure 9. Stiffness variation according to core material [18]

4.2.6. Influence of Core Thickness on Member Stiffness

Conducted numerical tests confirm that core characteristics have less impact on stiffness variation than skins ones. Moreover, for studied specimens, changing core thickness from 8 to 14 mm gives an irregular tendency of stiffness variation, for example, in the case of thin skins, increasing core thickness causes a reduction of compression stresses in bolted members which leads to the increase of K, although, when sandwich face sheets are thicker, higher constraints occur in joined parts which diminishes K identically to [14] where two aluminum members bolted with standard steel bolt show a stiffness diminution when grip length improves.

5. CONCLUSIONS

In the present paper, a multitude of bolted sandwich joints are modeled and tested numerically under three various preloads with a view to investigate their resulting displacements and analyze the effect of their multiple characteristics on the evolution of their member stiffness K. As well as, a 3D Finite Element Model based on two numerical modeling concepts is adopted in order to take into account simulation specificities of composite sandwich parts and bolt body. An analytical formulation is proposed for the equivalent modulus of each sandwich joint member. For that, a parametric equation representing the strain caused by the bolt preload is proposed and exploited to define the concerned modulus, then a search algorithm is performed in Excel software to investigate numerical results and define the parameters introduced for the determination of E_{eq}.

Moreover, the variation of member stiffness K in terms of joints characteristics is analyzed through a parametric study which confirms that sandwich facings impact greatly K because they carry the majority of stresses, generally, the growth of their thickness or their rigidity especially longitudinal elastic modulus along x-axis reduces recorded constraints and enhances the investigated K. Beyond, the influence of core is slighter than skins; the augmentation of core elastic modulus by 41.2% causes a maximum rise of stiffness that achieves 11.7%. Moderate preloads (0.06 kN and 0.5 kN) conserve approximately the same stiffness. Nevertheless, a considerably important clamping force (30 kN) improves K but intensifies shear effect which enhances the risk of core failure. Along these lines, greater bolt diameter enlarges the distribution of stresses and weakens their intensity which implies bigger member stiffness except for sandwich parts with rigid skins where concentrations of constraints caused by hole drilling can lead to a little drop in the concerned K.

NOMENCLATURES

1. Acronyms

FEM Finite Element Model

2. Symbols / Parameters

ρ: Material density (kgm^{-3})

E: Young's modulus (MPa)

E_b : Young's modulus of bolt (MPa)
E_a : Young's modulus along the *a*-axis (MPa), with $a \in \{x, y, z\}$
ν : Poisson's ratio
ν_{ab} : Poisson's ratio in the ab-plane, with $ab \in \{xy, xz, yz\}$
G_{ab} : Shear Modulus in the ab-plane (MPa), with $ab \in \{xy, xz, yz\}$
σ_y : Yield stress (MPa)
σ_t : Tensile strength (MPa)
ε_{eq} : Equivalent strain created by preload
σ_{eq} : Equivalent stress created by preload (Mpa)
α_{skins} : Volume fraction of sandwich skins
α_{core} : Volume fraction of sandwich core
$E_{z_{skins}}$: Young's modulus of skins along *z*-axis (Mpa)
$E_{z_{core}}$: Young's modulus of core along *z*-axis (Mpa)
$E_{x_{skins}}$: Young's modulus of skins along *x*-axis (Mpa)

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