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FE analysis of single-bolt composite bolted joint by means of a simplified modeling technique

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Abstract

The new Composite Bolted Joint Element (CBJE) is applied to the FE analysis of a single-lap, single-bolt composite bolted joint, allowing for important reductions of the computational burden while maintaining remarkable accuracy of results. The CBJE is a user-defined finite element representative of the elastic behavior of the region comprising the bolted joint and a portion of the surrounding composite plates. This modeling approach exploits radially disposed beam-shaped elements whose stiffness matrix is defined according to the analytical solution of the theoretical reference model of composite bolted joints, previously attained by the authors. This allows establishing the structural equivalence between the FE model and the theoretical reference model of the joint. A comparative investigation between a full detailed 3D FE model and a shell one featuring the CBJE of the single-lap joint is presented. It demonstrates the capabilities of the CBJE to synthesize low simulation time requirements and outcomes exactness.

Keywords: rectilinear orthotropic composite material; circular plates; bolted connections

1. Introduction

The finite element analysis of joints represents an arduous aspect of dealing with in mechanical design both from the modeling and the computational point of views, because of the different components comprising the joint and the numerous issues that a reliable simulation must take into account. Among the possibilities of mechanical joints, these considerations particularly regard composite bolted joints. Many works in the scientific literature debate this topic and, in this regard, papers concern diverse subjects in the field of composite bolted joints analysis, such as: analytical description of shear behavior (Kou et al. (2018); Zhao et al. (2019)), numerical assessment of failure behavior (Mandal and Chakrabarti (2015); Hu et al. (2018b)), experimental studies (Giannopoulos et al. (2017); Hu et al. (2018a)) and finite element analysis of joints (Chowdhury et al. (2016)).

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As outlined in these references, many physical phenomena, on different scales, should be taken into account in a comprehensive and accurate model of a composite bolted joint; this demanding task penalizes both the realization of an FE model and the computational time necessary for the analysis. Therefore, a reliable and efficient, from a computational standpoint, simulation tool can provide considerable benefits to the design phase.

In this order of ideas, the authors developed a user-defined finite element for the simulation of bolted joints connecting composite plates (CBJE). It can be employed for the structural analysis of the bolt and plate portions surrounding the bolt hole. As regards the FE modeling technique, the bolted joint region is replaced by two sub-elements connected through a system of rigid beams to a beam element with the bolt geometrical and material characteristics. Each sub-element consists of a set of beam-shaped stiffness matrix finite elements, available in all the principal FE commercial software, that allow the custom definition of the stiffness matrix terms.

Moreover, the theoretical reference model of composite bolted joint consists of a circular plate in composite material featuring rectilinear orthotropic material properties; the external edge of the plate is clamped, meanwhile the inner edge is connected to a non-deformable nugget. The analytical solution of this reference model is utilized for the definition of the beam-shaped element stiffness matrix so as to make a single beam-shaped element structurally equivalent to an angular sector of the theoretical reference model.

Consequently, based on the analytical solution of the theoretical reference model, the stiffness matrix is derived taking into account the main load conditions occurring on a bolted joint, i.e., in-plane load, transversal load, and in-plane bending moment. In the previous studies, the theoretical framework was based on Classical Laminate Plate Theory (Belardi et al. (2018b,d)), under the Kirchhoff-Love kinematic hypotheses. Anyway, in some circumstances, the thin-plate assumption can limit the usability of this simulation methodology and, as a consequence, the analytical approach for the solution of the theoretical reference model was further improved removing this restriction. Therefore, it was developed a theoretical framework founded on the First-order Shear Deformation Plate Theory, as described in Belardi et al. (2018c), where the displacement field is derived by means of an elaborate analytical procedure that makes use of Ritz method, needed to solve the three fundamental loading conditions considered.

Furthermore, the stiffness matrix terms of the proposed novel Composite Bolted Joint Element regarding the in-plane elastic behavior were derived in Belardi et al. (2018a); the first application of this FE modeling approach is reported in Belardi (2019) where it is employed for the simulation of a double-lap hybrid bolted joint. Then, the theoretical reference model formulation based on First-order Shear Deformation Plate Theory was utilized to entirely derive the stiffness matrix, including the terms related to the plate bending (Belardi et al. (2019)).

Here, the FE analysis of a single-lap, single-bolt joint is reported, and two FE modeling methodologies are compared: the 3D model one, taken as reference, and the simplified one consisting of shell elements and the novel CBJE; the comparison of results demonstrate a good degree of matching. In addition, the presented simulation technique is characterized by an elevated accuracy level in terms of composite bolted joint displacement field prediction and allows for a remarkable computational burden reduction in reference to 3D FE models.

2. FE modeling strategy of Composite Bolted Joint Element

The FE modeling strategy utilized in the present paper stems from the development of the Spot Joint Element, defined in Vivio (2009), where the concept of joint FE modeling based on the analytical solution of the theoretical reference model was originally presented. This modeling technique is applicable to shell FE models, and it makes use of a set of radial beams to replace a portion of preexisting shell elements mesh present in the overall FE model. Thus, a single beam element simulates the elastic behavior of an angular sector, with $\alpha_1 + \alpha_2$ angular extension, of the theoretical reference model, see Fig. 1. Classical beam elements were initially employed, and their stiffness properties were tailored to obtain the necessary values derived from the analytical solution.

The enhancement of the above-mentioned spot modeling technique is presented in Belardi et al. (2019). For the composite bolted joints simulation purposes, the finite element modeling technique makes use of beam-shaped stiffness matrix elements, in place of the classical beam elements. In fact, this typology of finite elements features greater flexibility of utilization since it allows a complete definition of an angular sector stiffness matrix, on both the inner and the outer edge Belardi et al. (2019). In particular, three fundamental load conditions acting on the theoretical reference model were analytically solved to define the stiffness matrix of CBJE: (*i*) in-plane load, (*ii*) transversal load,

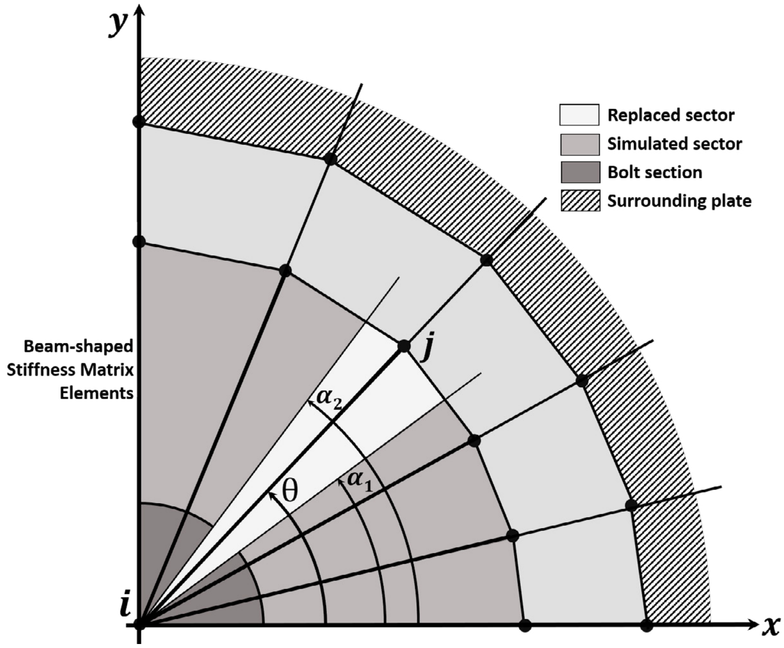


Fig. 1. Structure of the Composite Bolted Joint Element.

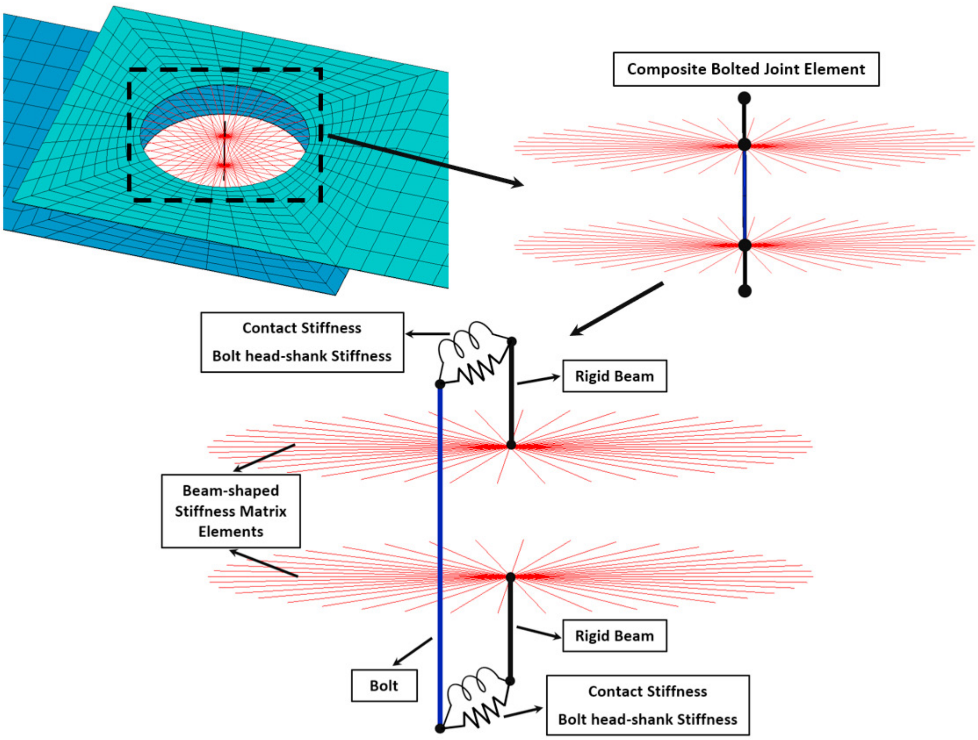


Fig. 2. FE structure of the Composite Bolted Joint Element (CBJE).

and (*iii*) in-plane bending moment. Both the displacement field and the stress resultants are employed to elastically characterize the joint; the obtained values of stiffness are then assigned to the beam-shaped elements.

Moreover, in order to discretize the bi-dimensional analytical solution to a one-dimensional FE model, the theoretical model is divided into angular sectors. Their elastic properties are attributed to a single beam-shaped element using proper stiffness values that must be defined for the degrees of freedom of the central node (node *i*) and the ones of the peripheral nodes of the CBJE (named nodes *j*). Then, the general definition of stiffness, i.e., the ratio between the applied force and the measured displacement when all remaining degrees of freedom are restrained, is utilized to transfer the analytical solution of the theoretical reference model to the CBJE. Thus, the CBJE structural behavior allows obtaining the desired equivalence with the analytical model.

The remaining elastic characteristics present in the bolted joint give their contribution to the CBJE as outlined in Fig. 2. Since both the shell elements and the stiffness matrix elements are modeled at the composite plates mid-surface, two rigid beam elements orthogonal to the plates are realized to delimit the beam element representing the bolt. Additionally, the bolt in-plane displacement degrees of freedom are connected to the rigid beams ones through spring elements capable of simulating the contact stiffness between the bolt shank and the hole of the plates; this phenomenon is modeled as a beam supported on an elastic foundation as explained in Kou et al. (2018). Then, further spring elements are employed to account for the bolt head-shank stiffness. The remaining beam degrees of freedom are coupled with the rigid beam ones employing constraint equations.

Furthermore, the procedure necessary to obtain the CBJE is recurring, and it can be stored into a macro to be employed in the principal FE commercial software packages.

3. Results

The present Section describes the outcomes of a comparative FE analysis of a single-lap, single-bolt composite bolted joint whose geometrical characteristics are reported in Fig. 3; both a 3D FE model and a shell model featuring the CBJE were realized and their outcomes compared. Besides, the left plate of the single-lap joint is clamped, whereas the right one is simply supported, on the same edge the external tensile force $F = 20$ kN is applied.

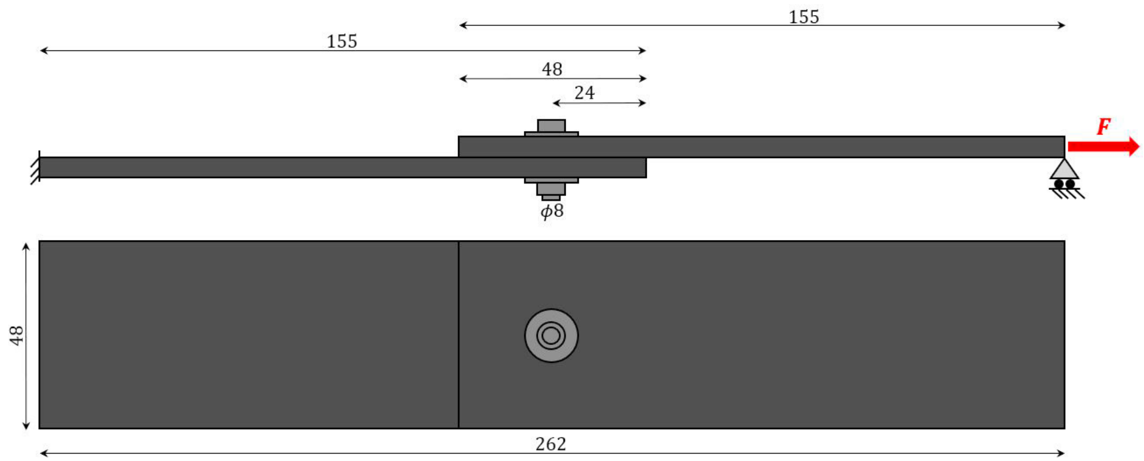
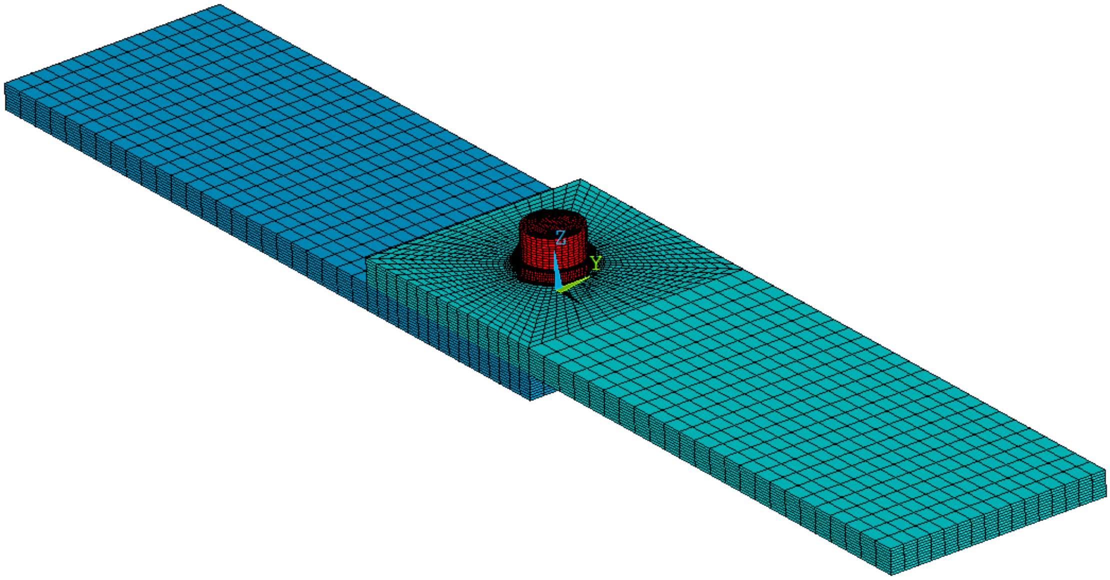


Fig. 3. Single-lap, single-bolt composite bolted joint object of the FE analysis.

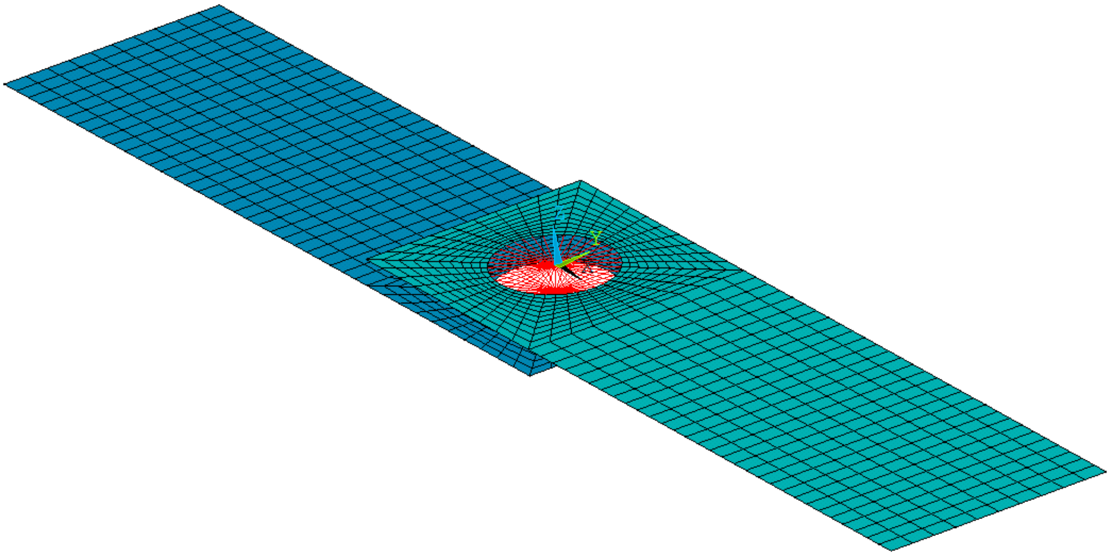
Table 1. Unidirectional fiber-reinforced layer stiffness properties McCarthy et al. (2005).

E_{11} [GPa]	E_{22} [GPa]	E_{33} [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	ν_{12} [−]	ν_{13} [−]	ν_{23} [−]
140	10	10	5.2	5.2	3.9	0.3	0.3	0.5

Furthermore, the single-lap joint is composed of two rectangular laminate plates featuring a quasi-isotropic lay-up: $[45/0/-45/90]_{5s}$. The plates thickness is $t = 5.2$ mm; meanwhile the thickness of the layers is $t_{lay} = 0.13$ mm; their orthotropic mechanical properties are reported in Table 1.



(a)



(b)

Fig. 4. Model of the single-lap, single-bolt composite bolted joint: (a) conventional 3D FE Model; (b) FE Model featuring the Composite Bolted Joint Element.

Table 2. Node and element numbers of 3D FE Model and FE model featuring the CBJE.

	3D FE Model	CBJE FE Model	Δ[%]
Nodes	47,137	1,547	−96.72
Elements	38,912	1,488	−96.18

The composite plates are fastened through a steel bolt featuring a diameter $d_{bolt} = 8$ mm, it is preloaded with a tensile stress $\sigma_{pre} = 250$ MPa; steel material properties are $E = 210$ GPa and $\nu = 0.3$. In addition, the joint features two steel locking washers. Also, being the friction coefficient between composite plates $\mu = 0.36$, the external force necessary to activate the components slipping is $F_s = 4.52$ kN. No clearance between the bolt shank and the hole of the plates is taken into account in the analysis.

Subsequently, a numerical study is set up in order to compare the outcomes of a conventional 3D FE model with the ones of a simplified FE model containing the CBJE, the FE models are shown in Fig. 4. In particular, the full detailed model is realized with 8-noded layered 3D elements, with 3 degrees of freedom per node, it features contact pairs between components and bolt preload. On the other hand, the simplified model is made up of 4-noded layered shell elements, featuring 6 degrees of freedom per node, and the joint area is realized with the CBJE.

The first conclusion to be drawn from the comparison of the two FE models regards their different computational burden, in fact, as reported in Table 2, the modeling approach based on the CBJE allows for an heavy reduction in the amount of both nodes and elements involved in the simulation, and, as a consequence, of the degrees of freedom. In addition, the possibility of combining the benefits, in terms of computational time reduction, proper of a shell FE model along with the accuracy and the high degree of fidelity typical of elaborate 3D models is the main advantage deriving from the employment of the Composite Bolted Joint Element.

Moreover, the notable decrease of analysis computational time does not entail a considerable loss of results accuracy. As a matter of fact, Fig. 5 depicts the curves relating the external force F and the displacement u_x evaluated along the direction of the applied load obtained with both 3D FE analysis and CBJE simplified analysis; the curve of the 3D FE Model reports the mid-surface displacement. The same diagram also shows the results obtained utilizing the shell-beam FE model (SB) that is widely employed in many industrial fields. Two distinct stages can be identified in the force-displacement curve of the single-lap joint under analysis. The first one is delimited by the origin of the axes and the point reaching the threshold value of external force F_{pre}; the second one is the curve sector characterized by the plates relative slipping, the global effect observed on the single-lap joint is a drop of stiffness.

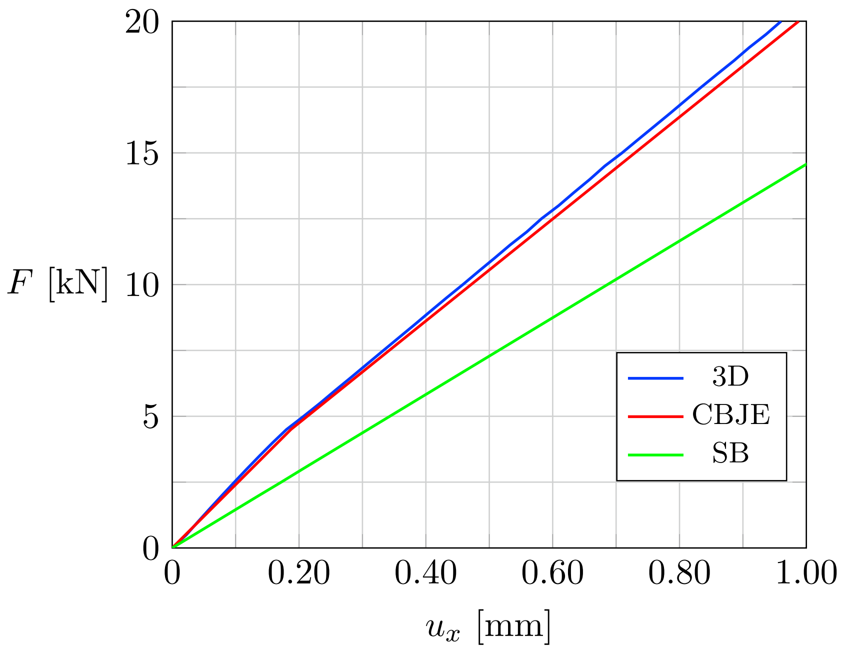


Fig. 5. Force-displacement curve of the single-lap, single-bolt composite bolted joint obtained by means of 3D model, CBJE model and shell-beam modeling.

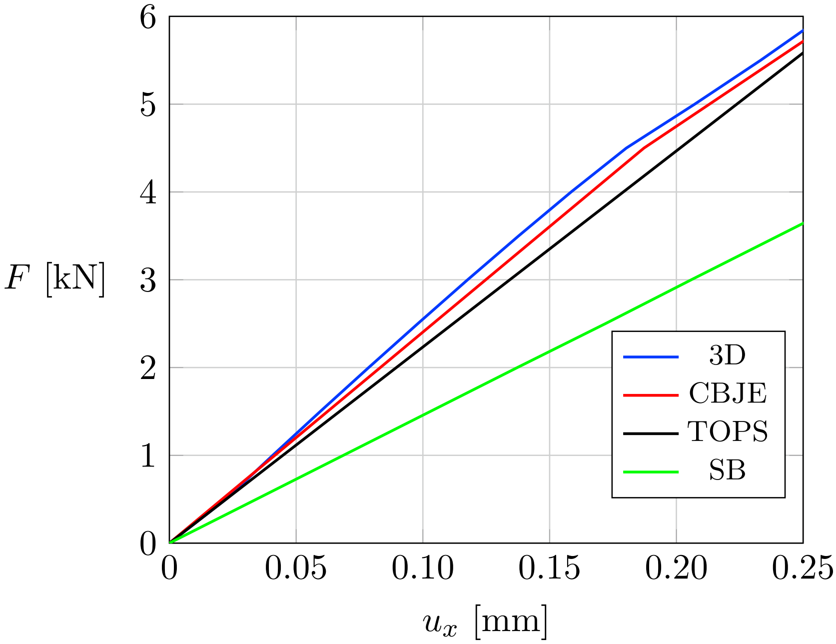


Fig. 6. Detail of the force-displacement diagrams before plates slipping F_{pre} is overcame.

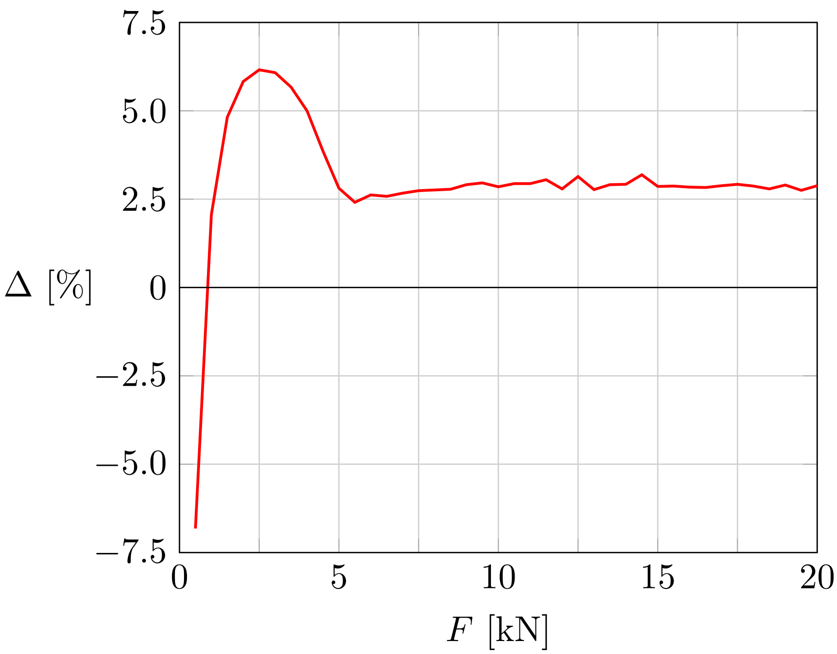


Fig. 7. Percentage error of force-displacement curve evaluated by means of CBJE FE model.

The force-displacement curve of CBJE FE model demonstrates a highly relevant degree of matching with the one of the 3D FE Model, both before the static friction force F_{pre} is reached and also after the external tensile force

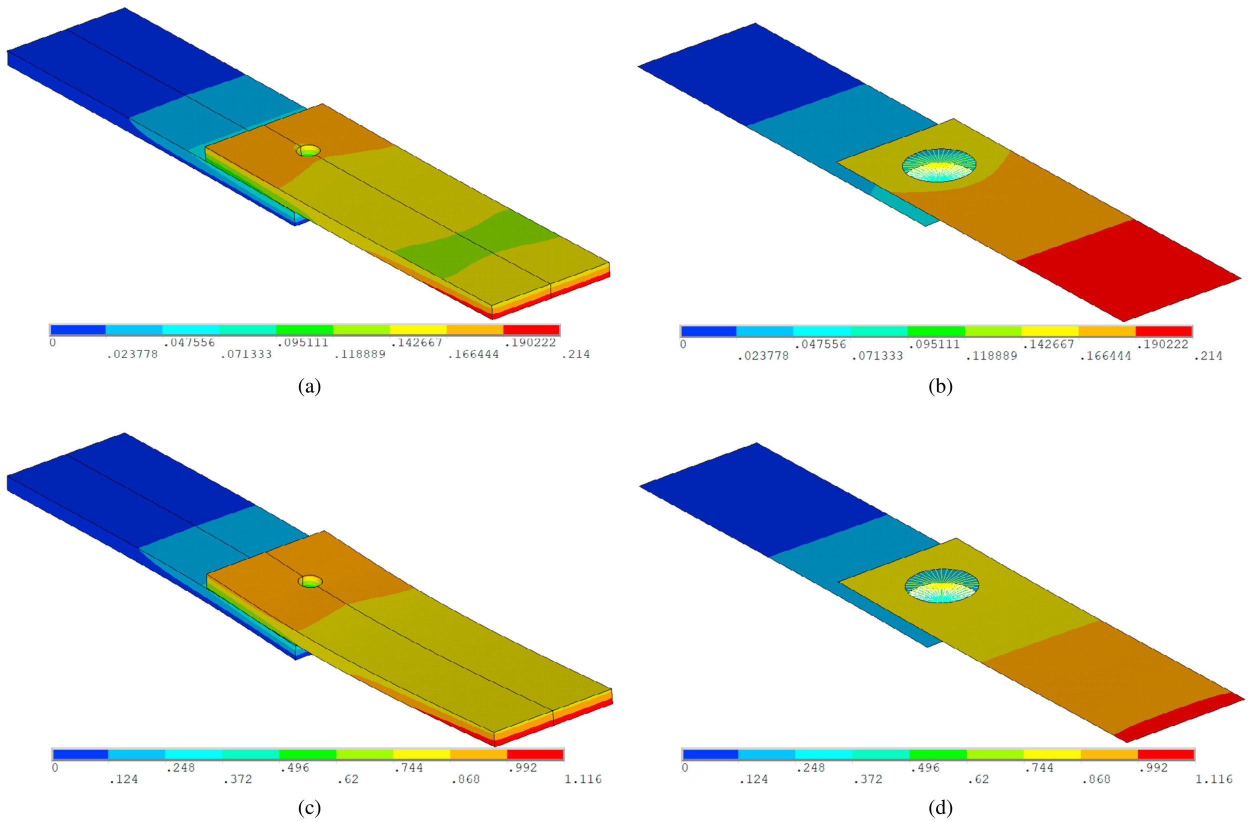


Fig. 8. Displacement along the external load direction obtained with 3D FE Model (left) and CBJE FE Model (right). (a) and (b) external traction force 4.5 kN, (c) and (d) external traction force 20 kN.

causes the plates reciprocal sliding. The capability of obtaining remarkable results even in the sliding stage of the force-displacement curve demonstrates that the CBJE FE modeling approach can take into account the friction effects of the joint.

On the contrary, the SB FE model, despite its wide diffusion, demonstrates a strong divergence of results in comparison with the 3D FE model ones. Indeed, this modeling strategy returns overrated values of displacement in all the range of external force variation. Consequently, it is not appropriate to obtain reliable insights into the composite bolted joint analysis.

Moreover, the detail of the initial force-displacement curves stage is reported in Fig. 6. As a further investigation, this Figure also outlines the curve obtained employing the classical version of the presented simulation methodology, i.e. the so-called TOPS Vivio (2009), which was updated according to the new composite bolted joint theoretical reference model. The comparative analysis between the CBJE and the TOPS is limited to the first stage of the force-displacement curve as the TOPS does not take into account the plates sliding. Nevertheless, this comparison allows to evidence that the modeling based on beam-shaped stiffness matrix elements is more suitable for the simulation of spot joint connections.

Then, Fig. 7 outlines the percentage error Δ as a function of the external force F between the force-displacement curve of CBJE FE model and the 3D FE Model one. This parameter turns out to be limited for any given value of external force, i.e., the CBJE FE Model is capable of identifying the single-lap joint behavior during the entire traction test.

Furthermore, Fig. 8 outlines the contour plots of the displacement measured along the direction of the external force F (x-axis of the Cartesian coordinate system of the FE model) evaluated by both the FE analyses methodologies. The contour maps are reported for two values of the external traction force: F = 4.5 KN, i.e., just before the beginning of the plates relative movement, and $F = 20$ KN that is at the end of the traction test. In addition, the bolt and the locking washers are not displayed in Fig. 8 in order to not alter the contour legend and make the comparison consistent. In both cases, the longitudinal displacement of the single-lap 3D FE model, evaluated at the mid-surface of the plates, is in very good accordance with the one obtained with the FE model featuring the CBJE.

Once more, the CBJE demonstrates significant capabilities of matching a reduced order of degrees of freedom with remarkable accuracy, since results it provides are in high agreement with those of high fidelity 3D FE models that in turn are onerous from both the modeling and the computational time standpoints. Besides, because of the relevant computational burden deriving from the high number of degrees of freedom required for the analysis, 3D modeling can hardly be utilized for the simulation of multi-jointed structures. Otherwise, this objective can be straightforwardly achieved through the employment of the CBJE whose formulation is intrinsically fitting for these analyses. Moreover, the CBJE revealed to be much more accurate than another simplified FE modeling technique, the shell-beam one that considerably underestimates the joint stiffness.

4. Conclusions

The results of a single-lap, single-bolt composite bolted joint FE analysis were presented. A conventional 3D modeling strategy of the joint, i.e., taking into account three-dimensional layered elements, contact between parts and bolt preload, was employed as a reference for a comparison with the Composite Bolted Joint Element modeling approach.

This new modeling approach makes use of the analytical solution of the composite bolted joint theoretical reference model to write the stiffness matrix of the beam-shaped elements composing the CBJE finite element assembly. Then, the bolt hole and the bolt head-shank stiffnesses are further considered by means of spring elements.

The displacement field obtained by the two models after a tensile traction test was compared in terms of the force-displacement joint curve. The test revealed a very notable degree of matching of the two methods results, and this result is even more remarkable taking into account the reduced computational order of the CBJE FE model that is substantially decreased with respect to the 3D model one.

Then, the Composite Bolted Joint Element technique was also compared with the shell-beam one because of its wide industrial diffusion. This analysis revealed that the CBJE FE model features greater accuracy.

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