Composite-to-metal multi-bolt joints: a simplified FE analysis method

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Abstract. This paper presents a modified version of the Composite Bolted Joint Element (CBJE) that can be employed for the finite element analysis of double-lap joints made up of metal and composite material plates. The CBJE makes use of the theoretical definition of composite bolted region that is solved to analytically define the behavior of the joint. The solution is utilized to obtain the stiffness of the bolted region and the bolt-hole contact stiffness that are transferred to the CBJE. The definition based on the analytical solution allows to balance the accuracy and the computational effort of the solution. The results of CBJE for hybrid double-lap joints is compared with a 3D FE solid demonstrating a highly remarkable matching.

1. Introduction
Numerous engineering applications require the connection of composite and metal components. Bolted joints represent the most utilized connection method to deal with flanges made up of different materials. The reason of this important spread mainly lies in the high load bearing capabilities of bolted joints, along with the ease of disassembling the joint. Additionally, bolted joints, if properly designed, are characterized by progressive and non-catastrophic failure modes, which allow bolts-load redistribution during damage progression. These features are compatible with scheduled maintenance inspections and, therefore, bolted joints are considered a reliable technique. These aspects explain the relevance of hybrid composite-to-metal bolted joints structural assessment.

The realization of prototypes and experimental studies provide detailed results about the behavior of bolted joints [1, 2]; anyway, the experimental campaigns can be expensive and unlikely performed on a wide range of configurations.

A fast assessment of the bolted joints can be obtained with the analytical methods. Basically, the joint is studied by means of a mass-spring model obtaining the governing equations [3, 4]. The main drawback of these approaches is the level of simplifications that are introduced and that can be reason of high approximations.

Nowadays, this task is primarily performed exploiting the finite element method. Three-dimensional models allow a detailed and accurate analysis of the joint [5, 6]. Nevertheless, a complete and detailed three-dimensional modeling approach is arduous, and the analysis is time consuming for both the modeling and the computational aspects, especially considering that
non-linear effects must be included. This particularly affects the preliminary design stage when different configurations must be explored and improved towards the optimization.

Conversely, the simplified FE approaches aim at the simulation of the bolted joint with a lower amount of computational resources [7, 8, 9]. To this end, a simplified modeling approach is outlined, it is funded on the solution of the bolted joint analytical model [10, 11, 12, 13]. The region surrounding the bolt is ideally split in angular sectors whose elastic properties are evaluated and assigned to a set of radially arranged beam-shaped stiffness matrix elements, that replace the angular sectors [14, 15, 16]. Also, a beam element is employed to model the bolt-shank, whereas two spring elements allow to consider: the friction effects, the bolt-hole clearances and the contact between the bolt and the plates. The proposed custom FE methodology allows the combination of an accurate definition of the joint stiffness properties along with a low computational burden. Furthermore, it is successfully compared with highly detailed 3D FE models.

2. FE modeling strategy for double-lap composite-to-metal joints

The FE modeling strategy is based on the concept of spot joint element defined by Vivio in Ref. [17]. The spot joint element makes use of a group of user-defined finite elements that are inserted in a global shell model to simulate a spot joint. The key idea of the methodology is the definition of a theoretical model including the joint and an annular portion of the surrounding plate, Figure 1. The model is clamped on the outer edge and connected to a rigid core representing the bolt. The action on the theoretical model of four typical load conditions is considered: (1) in-plane load, (2) transversal load \( P \), (3) radial bending moment, (4) torsional moment. Then, the reference model is analytically solved, and the analytical solution is utilized to assess the stiffness of the region.

In particular, the theoretical model is split into \( N \) angular sectors, the stiffness properties of each sector are evaluated and transferred to custom beam elements, see Figure 2, one for each sector, determining a set of radial beam elements.
Figure 2. Structure of the Composite Bolted Joint Element [15].

Moreover, each beam-shaped stiffness matrix element is equivalent in stiffness to the corresponding angular sector. The stiffness properties are evaluated through the ratio between the stress resultants and the generalized displacements, these quantities are obtained from the analytical solution of the theoretical model. In the case of metal plate, the theoretical framework exploits the hypothesis of isotropic material and it allows the obtainment of a closed form analytical solution. This solution is described in Ref. [17] along with the evaluation of the stiffness properties of the custom elements to be employed for metal plates. On the other hand, the theoretical model with the plate made up of composite material features rectilinear orthotropic material properties, i.e. stiffness properties variable with the angular coordinate $\theta$. In this case, a closed form solution is not achievable and the solution strategy is based on the application of the Ritz method to the principle of virtual displacements, as described in Refs. [10, 11, 12, 13]. Then, the upgraded version of the spot joint element for composite bolted joints, the Composite Bolted Joint Element (CBJE), was presented in Ref. [16] with the relative description of the stiffness matrix of the custom beam elements.

The configuration of the CBJE to be employed for the structural analysis of composite-to-metal double-lap bolted joints is shown in Figure 3. Specifically, the configuration of the double-lap joint is characterized by two metal outer plates and an inner composite plate. It follows that the stiffness matrix of the upper and lower groups of custom beam elements differs from the central one since the theoretical models are different.

Furthermore, there are other components building up the CBJE. The bolt shank is modeled with beam elements; these elements are connected to the upper and lower groups of custom beam elements through two rigid beam elements. This is necessary since the plates are meshed on their mid-surface. In addition, the connection between the beam elements of the bolt shank and the rigid beams is realized with spring elements. The spring elements $k_r$ are needed to simulate the interaction between the bolt head and the shank. The non-linear spring elements $k_m$ are necessary to model the bearing contact between the bolt shank and the holes of the metal plates and, in addition, the relative sliding occurring when the static friction force is reached. Then, a further non-linear spring $k_c$ with analogous properties connects the middle node of the bolt shank to the group of custom beam elements of the composite plate.
3. Results

The modified CBJE for double-lap bolted joints is tested on a three-bolt hybrid specimen with aluminum outer plates and a composite material inner plate. The geometry of the specimen is depicted in Figure 4, the thickness of the plates is: \( t_1 = 2.6 \text{ mm} \) for the outer ones and \( t_2 = 5.2 \text{ mm} \) for the inner one. The properties of the metal materials are reported in Table 1 and those of the composite layers in Table 2; the stacking sequence of the composite plate is \([45/0/-45/90]_5\).

In addition, the joint presents three titanium bolts with \( d_{\text{bolt}} = 8 \text{ mm} \) that are preloaded with a tension stress \( \sigma_{\text{pre}} = 100 \text{ MPa} \) and the bolt-hole radial clearance is equal to \( c = 10 \mu\text{m} \). Considering that the friction coefficient between the aluminum and the composite plates is \( \mu = 0.40 \), the static friction force that sticks together the plates is \( F_s = 12.06 \text{ kN} \).

Moreover, the double-lap joint is tested with a traction force \( F = 30 \text{ kN} \). As regards the boundary conditions, the left edge of the outer plates is fully constrained and the right edge of the inner composite plate is simply supported and loaded with the traction force \( F \).

The traction test is simulated with a shell FE model containing the CBJE for the bolted regions and with a high fidelity 3D model, that is the reference for the results verification. The shell model is composed of layered elements with 4 nodes and 6 degrees of freedom per node, whereas the 3D model presents the solid elements are 8-noded with 3 degrees of freedom per node. Regarding the 3D model, the composite plate is meshed using layered solid elements, it further contains contact elements to simulate the Hertzian contact between the bodies. Then, the two FE models are shown in Figure 5; the whole 3D depicted even though, considering the double symmetry of the double-lap joint, a quarter of the 3D model was analyzed.

Furthermore, despite the exploiting of the symmetries, the 3D model is considerably heavier.
Figure 4. Geometry of the double-lap three-bolt hybrid bolted joint.

Table 1. Elastic properties of the metal materials.

| Material | E [GPa] | ν [-] |
|----------|---------|-------|
| Aluminum | 70      | 0.30  |
| Titanium | 110     | 0.29  |

Table 2. Unidirectional fiber-reinforced layer stiffness properties.

| E₁₁ [GPa] | E₂₂ [GPa] | E₃₃ [GPa] | G₁₂ [GPa] | G₁₃ [GPa] | G₂₃ [GPa] | ν₁₂ [-] | ν₁₃ [-] | ν₂₃ [-] |
|-----------|-----------|-----------|-----------|-----------|-----------|---------|---------|---------|
| 140       | 10        | 10        | 5.2       | 5.2       | 3.9       | 0.3     | 0.3     | 0.5     |

from the computational standpoint. In this regard, Table 3 outlines the amount of nodes and elements composing the two FE models. The comparison between these modeling techniques reveals that the CBJE drastically reduces the simulation time that depends on the amount of degrees of freedom and, therefore, on the quantity of nodes and elements.

A first assessment of the CBJE accuracy is outlined in Figure 6, it is shown a comparison between the contour maps of the displacement $u_x$ obtained with both the FE models. The contour map of the CBJE model reports the displacement at the mid-surface of the plates. The distribution of displacement is very similar.

The CBJE methodology is capable of accurately evaluate the global stiffness of the double-lap joint. In fact, Figure 7 compares the load-displacement curves of the joint obtained with the two FE model, and it should be noted that the degree of accordance of the curves is remarkably relevant. In addition, the curves feature two stages: the first one presents higher stiffness and the plates are stuck together by the friction forces, the second one is characterized by lower slope...
Figure 5. Double-lap three-bolt hybrid bolted joint: (left) 3D model; (right) shell model with CBJE.

Table 3. Computational burden of double-lap three-bolt hybrid bolted joint modeled with the 3D elements and the CBJE technique.

|                | 3D FE Model | CBJE FE Model | ∆ [%] |
|----------------|-------------|---------------|-------|
| Nodes          | 65,976      | 4,248         | −93.56|
| Elements       | 67,052      | 4,302         | −93.58|

Figure 6. Contour of displacement $u_x$ in the load direction determined by 3D model and CBJE model.

determined by the slipping of plates and the radial clearance recover.

The proposed method founded on the CBJE can also determine the load distribution between the bolts. Figure 8 reports the distribution of the external load between the bolts. It can be seen that during the initial part of the traction test the external load is reacted by the friction force acting at the mutual interface between the plates, meanwhile the bolts do not share any amount of load. Once the maximum value of the friction force $F_s$ is equaled, the further increments of external load are reacted by the bolts and they produce the relative movement between the plates. In particular, the first bolt, i.e. Bolt 1, shares the highest portion of the applied load; it is followed by Bolt 3, whereas Bolt 2 carried the lowest amount of load. The amounts of
Figure 7. Diagram of load-displacement curves of the double-lap three-bolt joint determined by 3D model and CBJE model.

Figure 8. Distribution of bolt-load versus the joint displacement of the specimen, comparison of 3D model and CBJE model.
bolt-load are precisely assessed by the CBJE model, the differences with the 3D model are very limited. The reliable evaluation of the bolts-load allows for the accurate structural assessment of the joint.

4. Conclusions
In this paper, the extension of the CBJE methodology for hybrid composite-to-metal bolted joints is presented. The CBJE is a user-defined finite element, the characteristics of the elements derive from the theoretical reference model of bolted joint. The solution of the theoretical model is obtained in closed form solution, whereas the composite material theoretical model is solved exploiting the Ritz method.

This modified version of the CBJE is tested through the analysis of a hybrid double-lap joint, the results are compared with a 3D FE model. The main outcomes of the comparison are related to important computational savings which allows a reduction of the computational time. Then, the stiffness of the joint is accurately measured along all the load-displacement curve and the distribution of bolts-load is also precisely determined.

The combination of precision and low computational requirements is particularly advantageous during the first stage of the design process, in order to assess different configurations of the joint.

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