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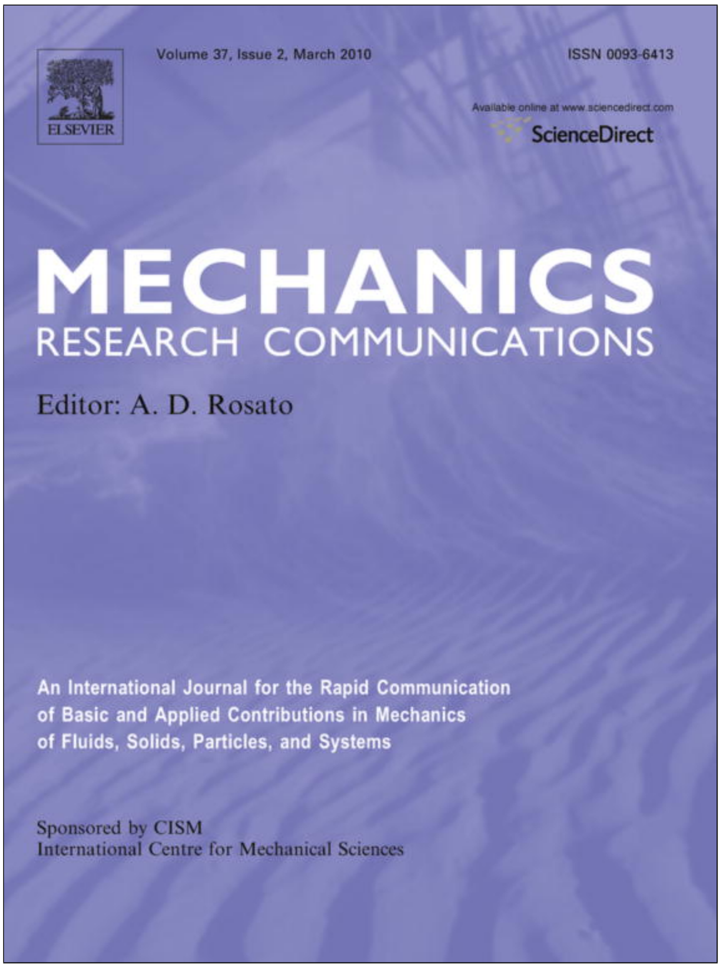


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# A preliminary numerical and experimental investigation on the shear stress distribution on multi-row bolted FRP joints

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ABSTRACT

The first results of a numerical and experimental investigation on the shear forces distribution in a bolted joint made entirely from FRP materials are presented. It is also proposed an experimental equipment for investigating the strains and stresses distributions around the holes of the connection as well as the bearing stresses at the interface between plate and steel bolt. A good agreement between numerical and experimental results allows to use the proposed testing set-up for analysing the bearing failure of several joint configuration with different lamination scheme, geometry and type of load.

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## 1. Introduction

The developments in building civil structures entirely out of composite materials have so far been towards the use of pultruded beams. Their employ would lead to a reduction of up to 70% in structural mass as well as guarantee reduced assembly time with minimal manpower without the need of using heavy mounting equipment.

Some of the first applications of FRP materials for complete bridge structures were in China 1982: a number of pedestrian bridges have been built but the first major bridge was the Miyun Bridge completed in September 1982 near Beijing, which carries full highway traffic. Another attractive bridge is the Xiangyong bridge in Chengdu which consists of a 4 m wide GRP deck suspended from a reinforced concrete arch.

Several bridges have been built also in the United States using fibre reinforced composites: the major part of these are of Glass-FRP or Carbon-FRP cellular type panels, overlain and glued, creating box sections. Others have been made of pultruded beams bolted or glued to each other: the most important include Tom's Creek Bridge (1996 – Fig. 1), Clear Creek Bridge (1996), Laurel Lick Bridge (1997), Wirkwire Run Bridge (1997), Bentley Creek Bridge (2000 – Fig. 2) and Over Deer Bridge (2001).

The first applications of such materials in Europe were carried out using an innovative modular glass reinforced polyester pultruded construction system, called ACCS, in the early 1990s. The most important structures built using the above-mentioned system were several bridges in Scotland, North Wales and England. It is worth mentioning Aberfeldy Bridge (1997 – Fig. 3), Bonds Mill Lift Bridge (1992), Bromley South Bridge (1992 – Fig. 4) and Parson's Bridge (1995). Aberfeldy Bridge is particularly interesting due to it being the first suspension bridge to be built entirely out of composite materials. In fact the framework and columns were made using the ACCS construction system while the cables were made from aramid fibres (Kevlar).

Other significant applications of composite materials in the field of civil engineering include various experimental structures. Two important examples include the Compaq Computer Corporation Building in Houston and the experimental Apple Computer Building in California. The Eyecatcher Building in Basilea (1999 – Fig. 5) is also particularly interesting due to the bolted and glued GFRP beams used.

The number of either provisional or permanent structures in Italy made from FRP elements is limited. Among the few structures worth mentioning, an inflatable pedestrian bridge made of bendable GFRP bars, erected in Rome (2000) for the Jubilee as well as the courtyard cover of the new courthouse in Pescara (Fig. 6), made entirely from glued and bolted pultruded beams can be included.

## 2. On the bearing failure of bolted joints

The increasing number of successful applications of FRP pultruded laminates in realizing civil structures, and their subsequent technological development, have attracted the attention of the international scientific community, with particular interest being given to understanding in greater detail the particular aspects connected to the use of new materials (Head, 1996).

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**Fig. 1.** Tom's Creek Bridge (1996).

**Fig. 2.** Bentley Creek Bridge (2000).

**Fig. 3.** Aberfeldy Bridge (1997).

**Fig. 4.** Bromley South Bridge (1992).

One of the main unresolved problem connected to the realization of this kind of structures is the design and verification of structural bolted joints.

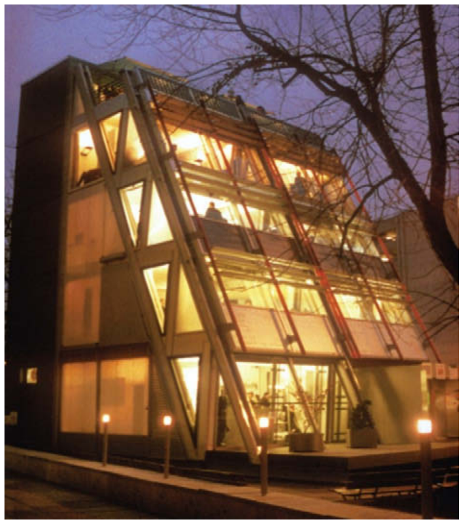

**Fig. 5.** Eyecatcher Building (1999).

**Fig. 6.** Courthouse in Pescara (1997).

As it is well known the results of the studies currently available in the technical literature on the FRP structural joints in the fields of aeronautical, mechanical and naval engineering cannot be directly applied to civil engineering. This is mainly due to the significantly different properties of the FRP used in the various applications as well as the different geometric scales.

For this reason, several theoretical as well as experimental studies have been recently carried out by researchers working in the field of civil engineering in relation to the various types of bolted joints (Hassan et al., 1996; Camanho and Matthews, 1997; Kelly and Hallström, 2004; Lie et al., 2000; Li et al., 2002; Ekh et al., 2005; Ekh and Schön, 2006; Vangrimde and Boukhili, 2002, 2003; Xiao and Ishikawa, 2005; Ireman, 1998; Yan et al., 1999; Starikov and Schön, 2002). The results of these studies have highlighted the failure modes of composite bolted joints, identifying the main factors that are responsible:

- ○ the values of the ratios between the geometric dimensions that characterise the joint (bolt diameter and spacing between holes, distance of the holes from the edges, width and thickness of the elements to be bolted);
- ○ matrix type and fibre nature;
- ○ the lamination scheme.

In this contest the author has investigated the bearing failure load of glass fibre epoxy laminates taking into account the effect of fibre inclination angle and laminates stacking sequence (Ascione

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et al., 2009, accepted for publication) with particular attention to a single bolt Glass-FRP connection.

The scope of this paper is to present a comparison between the first experimental and numerical results on the shear forces distribution in a bolted joint and to define an experimental equipment for studying the strains and stresses distributions around the holes of a such joint as well as the contact pressure at the interface between plate and bolt.

Once the experimental set-up has been defined, a wide investigation will be carried out on different types of bolted joints with different types of geometrical configurations, as well as different values of the diameter of the holes, the width of the joints, the distance of the holes from the edges and the distance between the bolts. Therefore, different types of FRP (glass and carbon) will be used, with both mono-directional and bi-directional (symmetrical stacking sequence) configurations.

The results of this research will be useful to design the joints of a real scale structure entirely made from Glass-FRP at the University of Rome "Tor Vergata", within the activities of the Research Project "*Structures in materials with microstructures. A challenge for modern civil engineering*" (MIUR Project no. 2005089782, 2005–2007). Such a structure will be used for the rehabilitation of a roofing construction of a monumental building shown in Fig. 7. The new roofing structure is truss-frame type with a length equal to twelve meter whose connections are realized with steel bolts.

Moreover, the testing set-up here presented will also be used to carry out an experimental investigation for validating the design formulations proposed in the technical document DT 205/2007 (CNR DT 205/2007, 2007) by the Italian National Research Council.

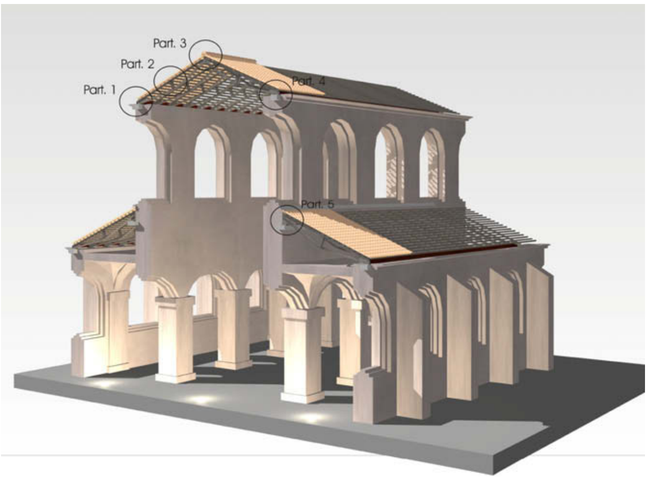


**Fig. 7.** Roofing structures view.

## 3. Experimental set-up

With the aim of carrying out the experimental investigation an equipment, consisting in a prototype of a double lap bolted joint made from composite bidirectional laminates (Fig. 8), has been designed by the author.

The geometry of the joint is characterised by two external plates, having dimensions 240 mm in length and 180 mm in width, and an internal one, with dimensions 480 mm × 180 mm. The thickness of the external and the internal plates are equal to 15 mm and 30 mm, respectively.

Distance between the holes is equal to 60 mm, while the distance of the holes from the edge is equal to 60 mm in the load direction and 30 mm in the orthogonal one, respectively. The bolts used are made of steel with 14 mm in diameter.

The material constituting the joint was fabricated by vacuum laminating eight or 24 sheets of unidirectional glass fibre and two plies of chopped strand mat (CSM), impregnated with epoxy resin (Ascione et al., 2009, accepted for publication). Its mechanical properties, summarized in Table 1, have been experimentally obtained by means of compression and tension tests performed in previous research (Ascione et al., 2009) by the author. In order to evaluate strains and stresses distributions near the hole of the joint, the sample has been instrumented by using electrical rectangular strain gages (C2A-06.062LR-120 Wishay MM) placed on both sides, as shown in Fig. 9.

A data acquisition system, consisting of three system 5100 Wishay MM switchboards set out in parallel with 60 extensometric channels (Fig. 10), has been used.

Moreover, the evaluation of the shear forces distribution between the bolts of the joint, has been obtained by using special pressure sensors positioned on the contact surfaces between bolts and GFRP plate, as shown in Fig. 11. Each sensor consists of a matrix of rows and columns of a semi-conductive material that changes its electrical resistance when force is applied to it. These rows and columns intersect to form sensing elements. By electronically scanning and measuring the change in resistance at each individual sensing element, the timing, force, and location of contacts on the sensor surface can be determined.

**Table 1**
Mechanical properties of the glass FRP bidirectional laminate.

| Property (experimental value) | Measurement unit | Value |
|---|---|---|
| Traction strength (0°) | MPa | 310 |
| Traction strength (90°) | MPa | 310 |
| Compressive strength (0°) | MPa | 381 |
| Compressive strength (90°) | MPa | 381 |
| Modulus of elasticity (0°) | MPa | 25,000 |
| Modulus of elasticity (90°) | MPa | 23,000 |

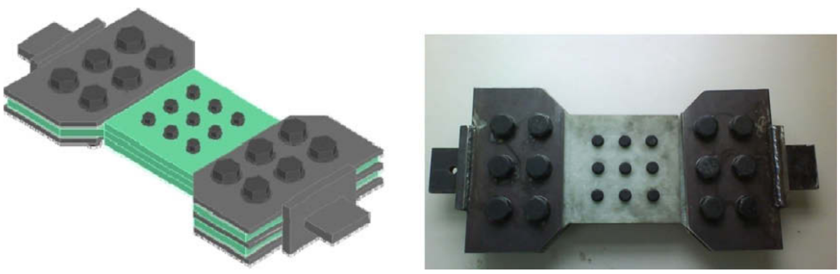

**Fig. 8.** Double lap bolted joint prototype.

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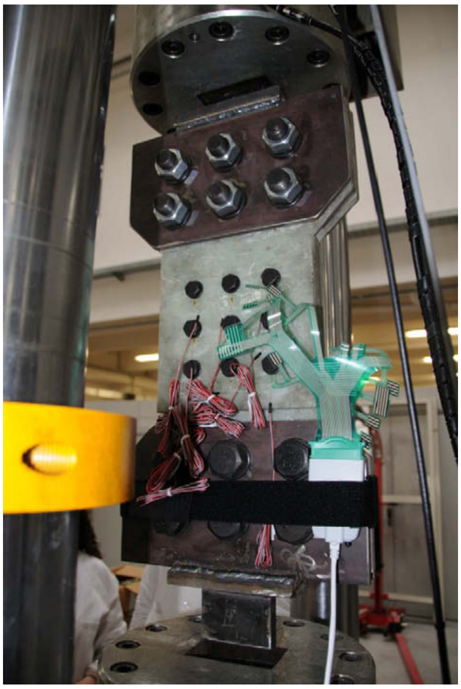

**Fig. 9.** Fixture attached to a universal 630 kN servo-hydraulic testing machine.

**Fig. 10.** Data acquisition system.

## 4. Preliminary finite element analysis

The first experimental results have been compared with those of a finite element analysis carried out by means of the software Strauss 7 of G + D Computing. In particular, the joint has been modelled by using eight-nodes orthotropic finite elements (bricks), as shown in Fig. 12. One-dimensional point-contact elements have been used to simulate the contact between the bolt and the FRP plates.

Fig. 13 shows the results of the finite element analysis in terms of normal stresses in the direction of the external load acting at the interface bolt-hole for the internal plate. Starting from the values of the bearing stress at the hole lateral surface, the shear force distribution has been evaluated relative to each row of bolts and for each bolt. The numerical results, in terms of percentage of the external load, for each of the nine bolts of the joint, are summarized in Table 2.

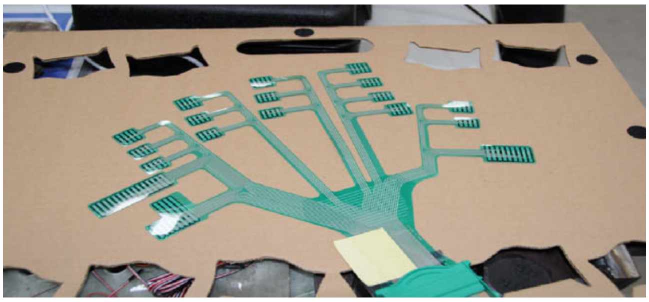

**Fig. 11a.** Pressure contact sensor.

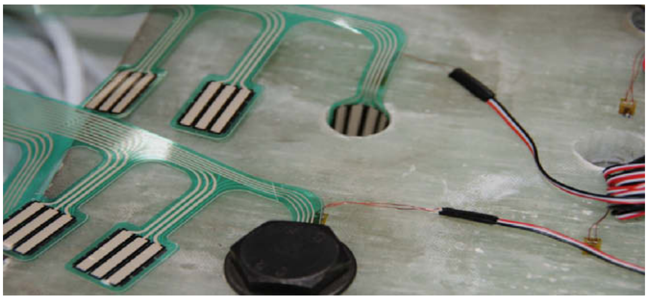

**Fig. 11b.** Positioning of sensors in the holes.

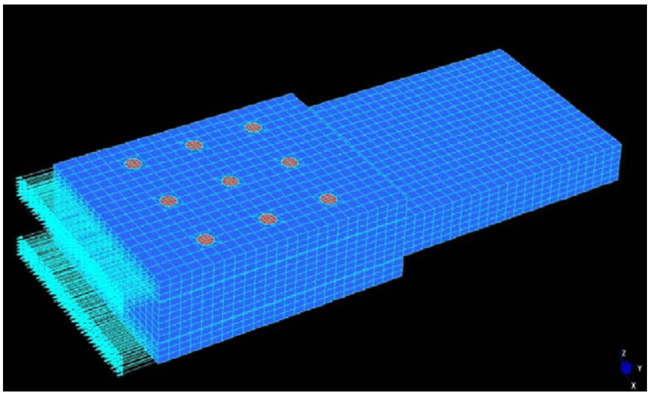

**Fig. 12.** Finite element mesh of the bolted joint.

**Table 2**
Shear force distribution coefficients (numerical results).

| Bolt/row | Row 1 (%) | Row 2 (%) | Row 3 (%) |
|---|---|---|---|
| Ext. | 12.1 | 9.4 | 12.1 |
| Int. | 11.8 | 9.2 | 11.8 |
| Ext. | 12.1 | 9.4 | 12.1 |
| Tot. | 36.0 | 28.0 | 36.0 |

It is interesting to observe that shear forces are not uniformly distributed between the bolts; in particular, the shear force distribution coefficients are equal to 28% for central row and to 36% for the external rows.

The numerical results above presented have been compared with those relative to the experimental ones relative to the bolted joint of Fig. 8. In details, test results have confirmed the numerical ones, as shown in Fig. 14, where the contact pressure distribution between hole and bolts for each bolt is qualitatively illustrated.

The experimental results, in terms of percentage of the external load, for each of the nine bolts of the joint, are summarized in Table 3.

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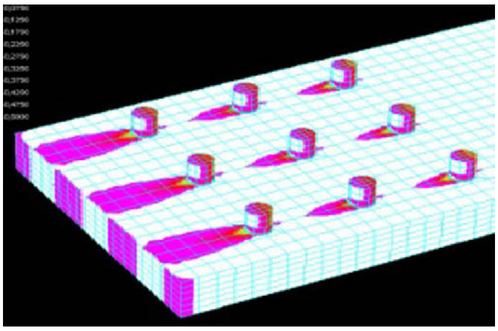

**Fig. 13.** Map of shear force distribution.

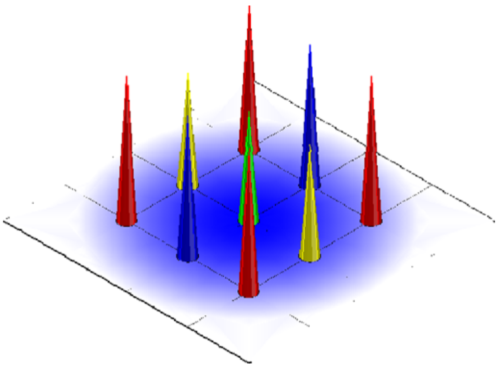

**Fig. 14.** Contact pressure map as recorded by the Tekscan system.

**Table 3**
Shear stress distribution coefficients (experimental results).

| Bolt/row | Row 1 (%) | Row 2 (%) | Row 3 (%) |
|---|---|---|---|
| Ext. | 12.8 | 8.9 | 12.9 |
| Int. | 11.5 | 8.2 | 11.4 |
| Ext. | 12.7 | 8.8 | 12.8 |
| Tot. | 37.0 | 26.0 | 37.0 |

The comparison between numerical and experimental results has highlighted a good agreement and gives the possibility to extend the aforementioned equipment and procedure test described, to several types of joints, varying the number of rows and the number of bolts per row.

## 5. Conclusions and further developments

In this paper the first results of a numerical and experimental investigation on the shear forces distribution in a double lap bolted joint made entirely from FRP materials are presented.

The comparisons between numerical and experimental results have shown a good agreement, in fact the differences, in terms of shear force distribution, are less than 5%.

The numerical results have been obtained by means of a finite element analysis: the joint has been modelled by using eight-nodes orthotropic finite elements (bricks), while the contact between the bolt and the FRP plates have been simulate by using one-dimensional point-contact elements.

The experimental results have been carried out by using an experimental equipment pointed out by the author for studying the strains and stresses distributions around the holes of the connection as well as the bearing stresses at the interface between plate and steel bolt.

Due to the good agreement between numerical and experimental prediction the proposed testing set-up will be used for analysing the bearing failure of several joint configuration with different lamination scheme, geometry and type of load.

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