BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LIX (LXIII), Fasc. 6, 2013
Secția
CONSTRUCȚII. ARHITECTURĂ

EXPERIMENTAL RESULTS REGARDING STRUCTURAL RESPONSE OF BOLTED AND HYBRID CONNECTIONS FOR PULTRUDED ELEMENTS

BY

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Received: November 7, 2013
Accepted for publication: November 29, 2013

Abstract. The experimental results obtained from testing three series of specimens consisting of bolted and hybrid single lap joints with two and four steel bolts are presented in this paper. Adherents are manufactured from glass fibre reinforced polyesters (GFRP) having 48 mm, respectively 100 mm width, and 6 mm thickness. By means of this experimental program the failure modes, ultimate strengths and displacements have been evaluated. In the case of joints with bolts tightened by hand, the best results have been obtained for specimens with four diameters edge distance. For specimens with 10 N.m and 20 N.m tightening torque applied to bolts, the values of the ultimate strengths are 16%...31% higher than those tightened by hand. The values of the hybrid connections (bolted/adhesively bonded) have registered an increase of the ultimate strengths of 5%...17% and a reduction of the ultimate displacements of 24%...60% in comparison with bolted joints.

Key words: bolted joints; hybrid joints; pultruded composites.

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1. Introduction

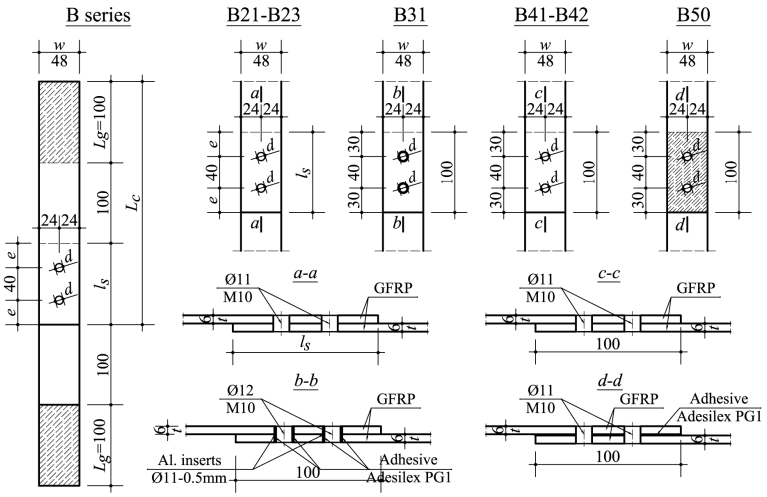
In the design of pultruded composite structures, joints are the most delicate regions that require great attention. The proper selection and calculation of these connections is highly dependent on the knowledge of the structural response as well as the mechanical and elastic characteristics of the components.

Bolted and adhesively bonded joints are the most common connections used in pultruded structures. Hybrid connections manufactured by combining adhesively bonded and mechanical methods minimize the characteristic weakness of a simple glued or bolted joint. In hybrid connections, the bolts reduce the peeling stresses and delay the failure initiation of the adhesive layer, while the failure strengths are governed by the strength of the adhesive before major debonding.

The structural response of bolted and hybrid single lap joints with two and four steel bolts and glass fibre reinforced isophthalic polyesters (GFRP) adherents is evaluated in this study. The instrumentation of the specimens has allowed the determining of the ultimate strengths and of the ultimate displacements, as well as the identification of the failure modes.

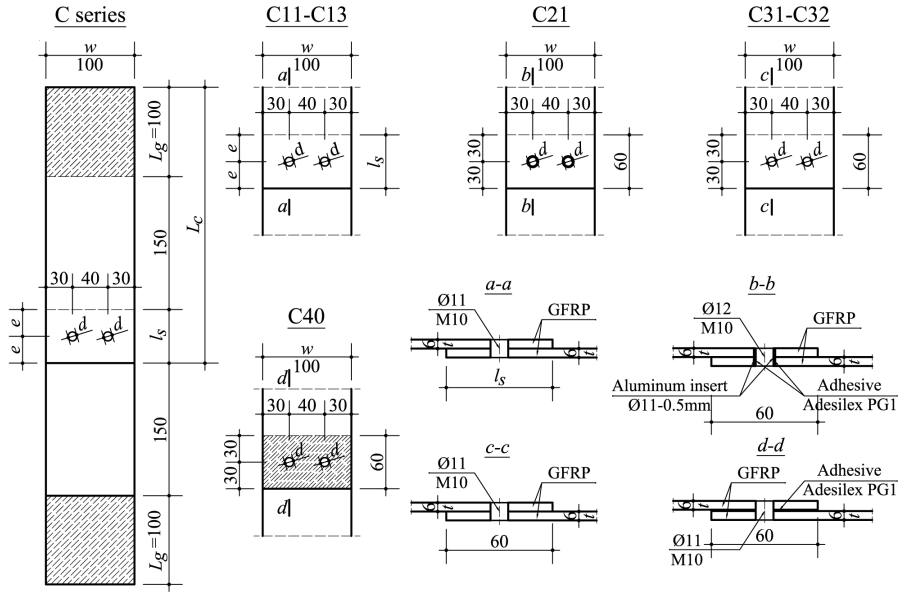
2. Experimental Program

Three series of specimens consisting of bolted and hybrid joints have been tested for the experimental program. The geometric characteristics of the samples are presented in Figs. 1,..., 3.



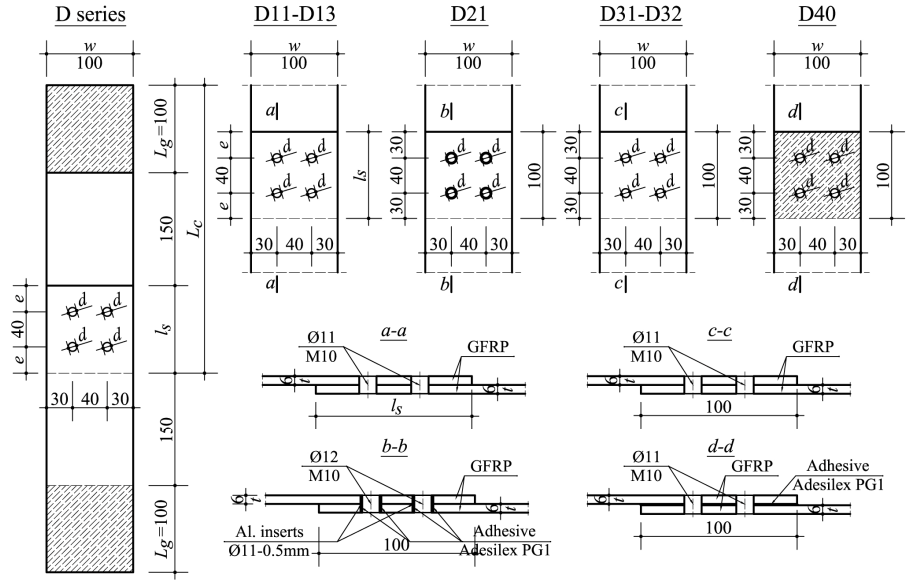
L_C = 300, 320, 340 mm; L_g = 100 mm; t = 6 mm; w = 48 mm; $w/d \approx 5$; e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67; l_S = 100,120,140 mm; Steel bolts M10 gr. 8.8; Aluminum inserts Ø11-0.5mm; Adhesive Adesilex PG1;

Fig. 1 – Specimen geometry for the B series (dimensions in mm).



L_c = 310, 330, 350 mm; L_g = 100 mm; t = 6 mm; w = 100 mm; w/d = 5; e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67; l_s = 60,80,100 mm; Steel bolts M10 gr. 8.8; Aluminum inserts Ø11-0.5mm; Adhesive Adesilex PG1;

Fig. 2 – Specimen geometry for the C series (dimensions in mm).



L_c = 350, 370, 390 mm; L_g = 100 mm; t = 6 mm; w = 100 mm; w/d = 5; e/d = 3,4,5 = 30,40,50 mm; d/t = 1.67; l_s = 100,120,140 mm; Steel bolts M10 gr. 8.8; Aluminum inserts Ø11-0.5mm; Adhesive Adesilex PG1;

Fig. 3 – Specimen geometry for the D series (dimensions in mm).

Each series consists of four subseries with seven samples having bolted and hybrid joints with two (B, C series) and four steel bolts (D series).

Adherents are manufactured from *E*-glass fibres reinforced isophthalic polyesters. The preparation of specimens and the mechanical and elastic characteristics for the employed materials has been described in detail in a previous study carried out by the authors (Popoaei, 2012).

Specimens have been tested in a 1,000 kN universal testing machine (Fig. 4), the speed of the tests having been set at 2 mm/min. crosshead movement according to ASTM D5868-01, D5961-13 and D6873-08.

The forces and displacements in the tested specimens have been measured using a load cell and linear variable differential transducers (LVDT).

Fig. 4 – Universal testing machine.

3. Experimental Results

During the tensile tests the forces and displacements in the specimens have been monitored using the integrated load cell and linear variable differential transducers of the testing machine.

3.1. Bolted and Hybrid Joints with Two Serial Bolts – B Series

The B series consisted of seven specimens with bolted joints (B2), bolted joints with holes consolidated with bonded aluminium inserts (B3), bolted joints with 10 N.m, 20 N.m tightening torque (B4) and adhesively bonded – mechanical joints (B5).

The failure modes (Fig. 5) identified for bolted joints are shear out for specimens with $e = 3d$ and bolt pulling through laminate for samples with $e = 4d$, $5d$. In the case of hybrid joints, failure occurs by interface failure between adhesive and adherents preceded by shear out or composite delamination.

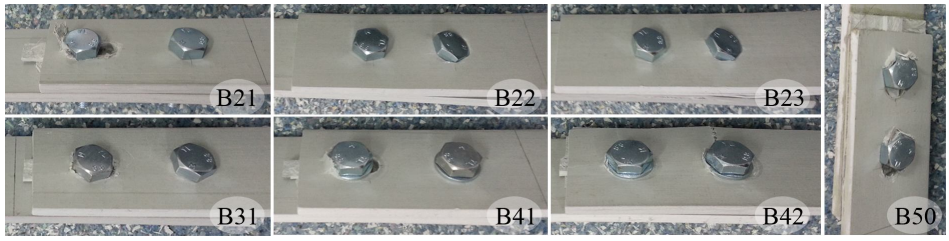


Fig. 5 – Failure modes for the B series specimens.

The average force *vs.* displacement curves and the experimental results for the B series specimens are presented in Fig. 6 and Table 1.

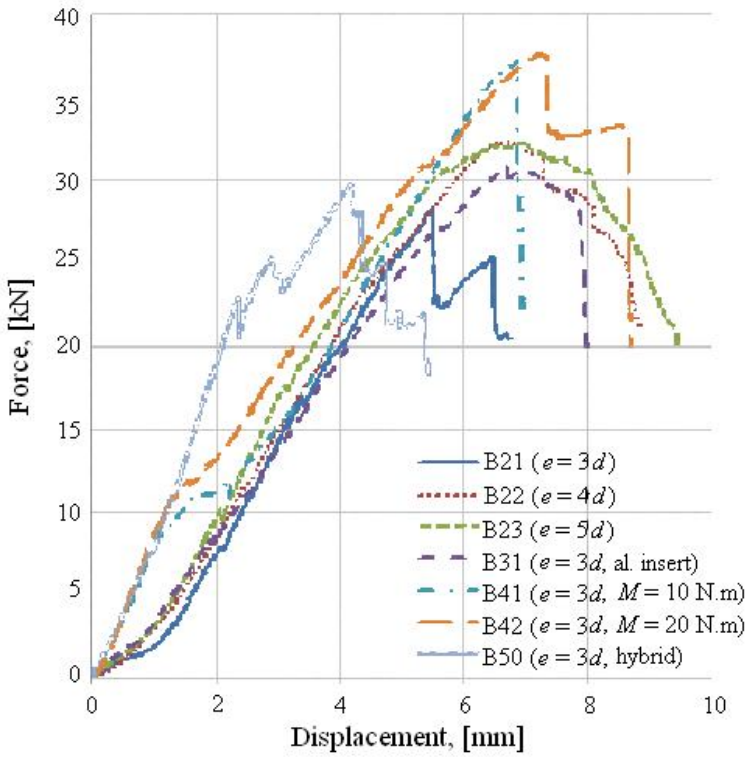


Fig. 6 – Force *vs.* displacement for the B series specimens:
e – edge distance; d – bolt diameter; M – tightening torque.

Table 1
Experimental Results for the B Series Specimens

Specimen	Ultimate force, [kN]	Ultimate displacement, [mm]
*B*21	28.29	5.49
*B*22	32.30	6.74
*B*23	32.21	7.00
*B*31	30.89	6.68
*B*41	37.16	6.86
*B*42	37.58	7.19
*B*50	29.74	4.17

The best results for the B2 subseries have been obtained for samples with $e = 4d$ if edge distance is considered. If compared with the B2 specimens, the preloaded joints (B4) have recorded an increase of the ultimate strengths of 31% and 5% for hybrid joints, respectively, as well as a decrease of the ultimate displacements of 24%.

3.2. Bolted and Hybrid Joints with Two Parallel Bolts – C Series

For the C series, seven specimens with the same type of bolted and hybrid joints used in the case of the B series have been tested. The failure modes for the C series are presented in Fig. 7. The identified failure modes are shear out for specimens with $e = 3d$ and $4d$ and bolt pulling out through laminate for samples with $e = 5d$. The failure mode of hybrid joints has occurred by interface failure between adhesive and laminate preceded by shear out.

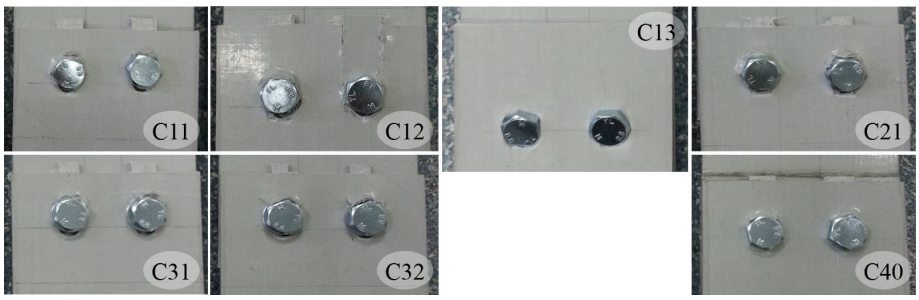


Fig. 7 – Failure modes for the C series specimens.

The average force vs. displacement curves and the experimental data values for the C series specimens are presented in Fig. 8 and Table 2.

For the C1 subseries the best results have been obtained for C12 samples with $e = 4d$. In the case of specimens with 10 Nm tightening torque (C31), the ultimate strengths have increased by 23% and the ultimate displacements have decreased by 16% if compared with the C11 subseries.

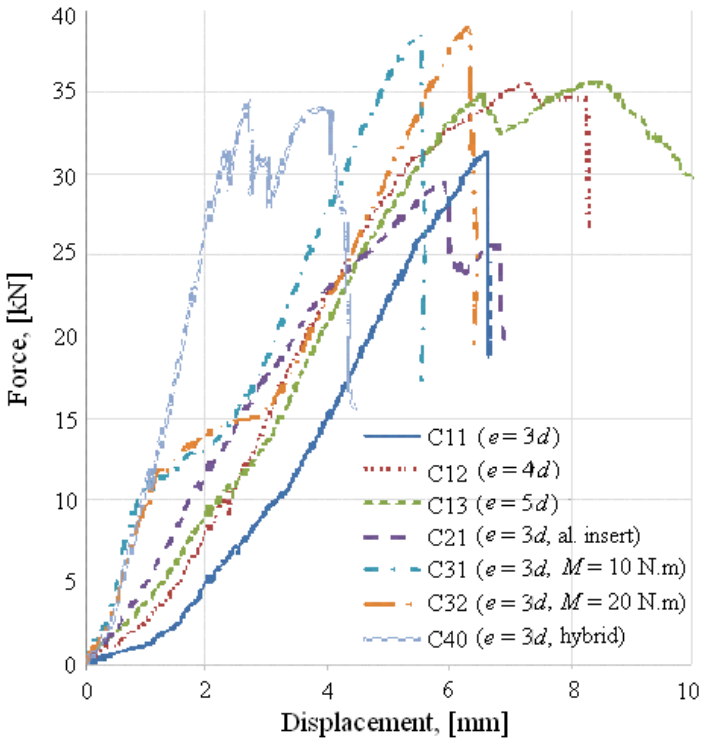


Fig. 8 – Force *vs.* displacement for the *C* series specimens:
e – edge distance; *d* – bolt diameter; *M* – tightening torque.

If compared with the C11 subseries, the hybrid connections (*C*40) have recorded an increase of the ultimate strengths of 10% and a reduction of the ultimate displacements of 60%.

Table 2
Experimental Results for the C Series Specimens

Specimen	Ultimate force, [kN]	Ultimate displacement, [mm]
C11	31.26	6.62
C12	35.64	7.23
C13	35.68	8.41
C21	29.57	5.85
C31	38.58	5.51
C32	39.16	6.32
C40	34.50	2.68

3.3. Bolted and Hybrid Joints with Four Holes – D Series

The D series consisted of testing seven specimens with different joint configurations having bolted connections with bolts tightened by hand and preloaded, hybrid joints (adhesively bonded – mechanical) and samples with holes consolidated with bonded aluminum inserts.

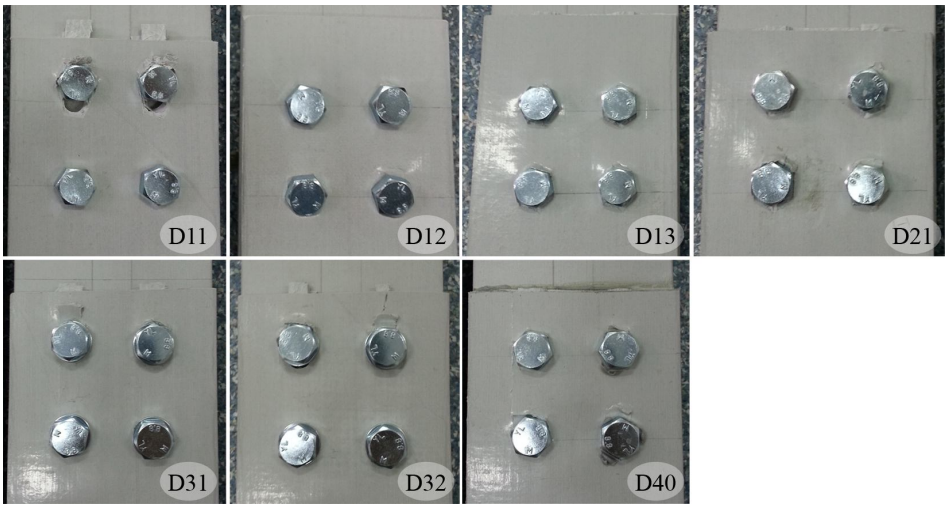


Fig. 9 – Failure modes for the D series specimens.

The failure modes of the D series specimens are presented in Fig. 9. For the D1 subseries the identified failure modes are shear out for specimens with $e = 3d$ and bolt pulling out through the laminate for $e = 4.5d$. In the case of hybrid joints failure occurs by adhesive or interface failure preceded by shear out.

The experimental results are presented in Table 3, while the average force – displacement curves have been plotted in Fig. 10.

Table 3
Experimental Results for the D Series Specimens

Specimen	Ultimate force, [kN]	Ultimate displacement, [mm]
D11	60.01	7.22
D12	68.54	8.97
D13	65.74	8.44
D21	55.18	9.03
D31	74.17	7.54
D32	69.65	8.09
D40	70.41	5.44

The best results have been obtained for hybrid (D40) and preloaded connections (D31).

The experimental results have shown an increase of the ultimate strengths of 17% and a reduction of the ultimate displacements of 24% for hybrid joints (D40) if compared with D11 specimens.

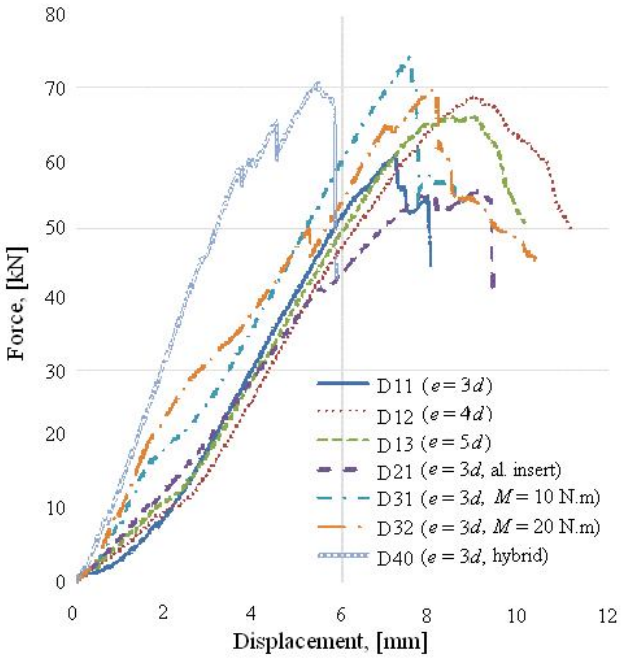


Fig. 10 – Force *vs*. displacement for the D series specimens:
e – edge distance; *d* – bolt diameter; *M* – tightening torque.

4. Conclusions

This study has investigated the structural response of single lap bolted and hybrid joints with two and four steel bolts having pultruded glass fibre reinforced isophthalic polyesters adherents. The failure modes, the ultimate strengths and the displacements have been evaluated by means of this experimental program.

For the specimens with bolted joints (B2, C1 and D1), the best results have been obtained in the case of samples with $e = 4d$.

Improving the performance of bolted joints using bonded aluminum inserts has been found to be a non-feasible method in case of single lap bolted joints with GFRP adherents.

The experimental results have shown an increase of the ultimate strengths of 16%…31% for specimens with tightening torque applied to bolts in comparison with those tightened by hand.

The hybrid connections have recorded an increase of the ultimate strengths of 5%...17% and a decrease of the ultimate displacements of 24%...60% when compared with bolted joints.

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REZULTATE EXPERIMENTALE PRIVIND RĂSPUNSUL STRUCTURAL AL ÎMBINĂRILOR CU ŞURUBURI ŞI HIBRIDE AL ELEMENTELOR PULTRUDATE

(Rezumat)

Se prezintă rezultatele experimentale obţinute în urma testării a trei serii de epruvete compuse din îmbinări mecanice şi hibride cu şuruburi realizate prin suprapunere. Aderenţii sunt fabricaţi din poliesteri armaţi cu fibre de sticlă (CPAFS) cu lăţimea de 48 mm, respectiv 100 mm, şi grosimea de 6 mm. În cadrul acestui program experimental sunt evaluate modurile de cedare, forţele ultime şi deplasările ultime. În cazul îmbinărilor cu şuruburi strânse cu mâna, rezultatele cele mai bune s-au obţinut pentru epruvetele cu distanţa de patru diametre măsurată din axul găurilor până la capătul piesei. Pentru probele cu momente de strângere 10 N.m şi 20 N.m valorile forţelor ultime sunt cu 16%...31% mai mari decât cele strânse cu mâna. Valorile obţinute pentru îmbinările hibride (mecanice – adezive) au înregistrat o creştere a forţelor ultime cu 5%...17% şi o reducere a deplasărilor ultime cu 24%...60%, când sunt comparate cu îmbinările mecanice.