The influence of bolt diameter on the bearing failure load of glass fibre/epoxy bolted laminates: an experimental investigation

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Abstract

The paper presents the experimental results on the influence of the bolt diameter on the bearing failure load of glass fibre/epoxy (GFRP) bolted laminates. Significant reductions in pin-bearing ultimate load when bolt diameter decreases are highlighted. Two different types of laminates have been tested: unidirectional and bidirectional.

1. Introduction

The noteworthy mechanical properties of Fibre Reinforced Polymer (FRP) materials, as for instance high values of rigidity/weight, resistance/weight ratios and high corrosion resistance, have made very interesting their use [1-2] in the area of civil engineering, substituting or being integrated with traditional materials. In the last years the design and verification of structural joints (both adhesive and bolted) has become an important theme, for these applications, not been yet adequately understood.

With reference to plate-to-plate connections with double lap-shear configuration and a single bolt the typical failure modes are summarized below [3]:

1) net-section failure;
2) shear-out failure;
3) pin-bearing failure;
4) fastener shear failure.

In particular, the third one has attracted the attention of the international scientific community, as confirmed by the great number of researches carried out during these last years [4-12]. The results of these studies have highlighted that the pin-bearing failure mode of FRP depends on the following main factors:

- joint geometry: bolt diameter (*d*), plate width (*w*), end distance (*e*) and thickness of the composite laminates (*t*);
- matrix type and fibre nature;
- fibre inclination angle;
- stacking sequence of the laminates.

In [12] the influence of the fibre inclination angle and stacking sequence on the pin-bearing failure load of GFRP plates connected with a single bolt has been investigated by the authors. To perform the experimental investigation, a pin-bearing test set-up was developed.

The objective of this paper is to extend the experimental study in order to investigate the influence of bolt diameter on the pin-bearing failure load of glass fibre reinforced composite laminates.

2. Experimental set-up

2.1 Materials

In order to perform the experimental study, the three different types of symmetrical laminates already studied in [12] have been tested. All of them were fabricated by vacuum laminating 8 or 24 sheets of unidirectional glass fibre and two plies of chopped strand mat (CSM), impregnated with epoxy resin. Their thickness, stacking sequence and volume fractions of fiber and matrix are briefly described below.

Type 1 Laminate. This laminate was constructed from eight equally oriented plies of GFRP $[CSM/0_4]_S$. The volume fractions of fibres and matrix of type 1 laminate were approximatively equal to 60% and 40%, respectively, and its thickness was equal to 10mm: 1mm for each CSM layer and 1mm for each 0-degree direction layer.

Type 2 Laminate. This laminate was constructed according to the stacking sequence $[CSM/0_6/90_6]_S$. In detail, it was fabricated using four ply groups, two made of six plies in the 0-degree direction, and the other two made of six plies in the 90-degree direction. The volume fractions of fibres and matrix of type 2 laminate were approximately equal to 65% and 35%, respectively, and its thickness was equal to 12mm: 1,2 mm for each CSM layer and 0.4mm for each 0 (90)-degree direction layer.

Type 3 Laminate. This laminate was fabricated according to the laminating sequence $[(CSM/0_3/90_3)\ _2]_S$. In detail, it was fabricated using eight ply groups, four made of three plies in the 0-degree direction, and the other four made of three plies in the 90-degree direction. The volume fractions of fibres and matrix of type 3 laminate were approximately equal to 65% and 35%, respectively, and its thickness was equal to 12mm: 1.2 mm for each CSM layer and 0.4mm for each 0 (90)-degree direction layer.

The mechanical properties of all laminates were determined by the authors through compression and traction tests, and the results are reported in Table 1 and 2, in terms of mean values. For a more detailed description see [12].

Table 1. Mechanical Properties of the GFRP type 1 laminate

Property (experimental mean values)	**Value [MPa]**
Tensile Limit Strength, 0°	222
Tensile Limit Strength, 90°	71
Compressive Limit Strength, 0°	201
Compressive Limit Strength, 90°	81
Modulus of Elasticity, 0°	28400
Modulus of Elasticity, 90°	11200

Table 2. Mechanical Properties of the GFRP type 2 and 3 laminates

Property (experimental mean values)	**Value [MPa]**
Tensile Limit Strength, 0°	310
Tensile Limit Strength, 90°	310
Compressive Limit Strength, 0°	381
Compressive Limit Strength, 90°	381
Modulus of Elasticity, 0°	25000
Modulus of Elasticity, 90°	23000

3. Test analysis

For this study have been made GFRP square samples, 500mm wide (Fig. 2). Each specimen was characterized by the presence of two holes: the first one (*hole 0*) was located at the centre, while the second (*hole i*) near the edge of the specimen in order to obtain a pre-established value of the fibre inclination angle, α, between the direction of the external applied force, coincident with the straight line passing through the centre of the two above mentioned holes, r_{0i}, and the 0° direction [12].

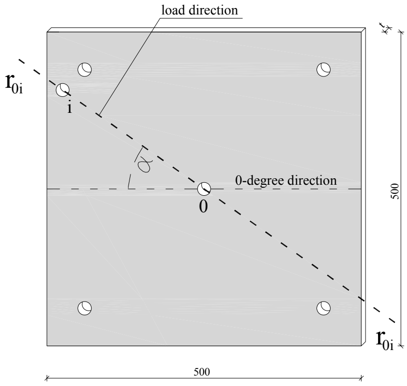

Fig. 1: GFRP specimen: geometry *(dimensions in mm)*.

The following sixteen values of α were considered for type 1 laminate: 0°, 1°, 3°, 5°, 7°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 60°, 75° and 90°. Instead, for type 2 and 3 laminates seven values were considered for α: 0°, 1°, 5°, 20°, 25°, 45° and 90°.

The central hole is 21mm in diameter and, in order to investigate the effects of the bolt diameter on the pin-bearing capacity of the laminates, three different bolts were produced whose (measured) diameters were: 18, 19 and 20 mm.

The pin-bearing experimental set-up is shown in Fig. 3. It was composed of two couples of square steel plates measuring 500mm wide and 50mm thick, with a centre hole of 300mm in diameter. Each steel plate had four corner holes corresponding to the holes made on the edges of the GFRP laminates (Fig. 2). More details are reported in [12].

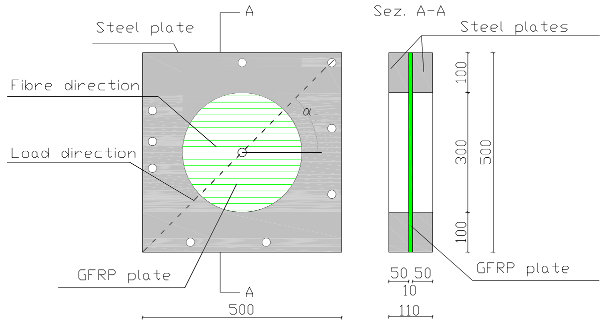

Fig. 2: Glass composite plate (GFRP) and steel plates (*measured in mm*).

This fixture was attached to a 630 kN load cell of a Shenck Hydropuls servo-hydraulic testing machine (Fig. 3) and the load was applied at a constant grip displacement speed of 9.9×10^{-3} mm/sec.

Fig. 3: Fixture attached to Shenck Hydropuls servo-hydraulic testing machine.

To measure the pin-bearing strain, all the laminates were equipped on both sides (to check the absence of flexural effects) with ten rectangular temperature self compensated strain gages (Vishay MM C2A-06-062LR-120), placed as shown in Fig 4.

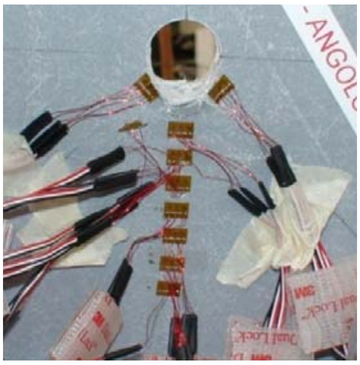

Fig. 4: Scheme of the strain gages around the central hole of the GFRP laminate (post failure photo illustrating the debonding of one of the strain gages – α=0°).

During the tests, load, displacements and strain were recorded by an automatic data acquisition system consisting of three "System 5100 Vishay MM" switchboards, with 60 extensometric channels set out in parallel. Data obtained during the tests were subsequently elaborated using the *StrainSmart* software.

The pin-bearing failure load has been evaluated by means of the load-displacement curve. In particular, it corresponds to the first peak value of the aforementioned curve, as shown in Fig. 5.

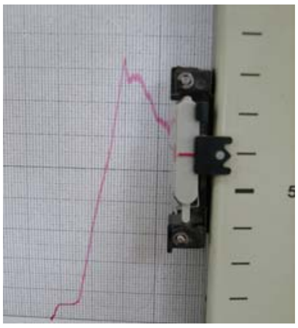

Fig. 5: Evaluation of the pin-bearing failure load.

4. Result and discussion

In this section the pin-bearing failure load values, $F_u^{(\alpha)}$, for all the GFRP laminates are presented and discussed.

Type 1 Laminate: Figure 6 shows the curves of $F_u^{(\alpha)}$ varying the angle α and the bolt diameter (*d*) for type 1 laminate. It is worth noting that the curves have been obtained using average values. In particular, for each value of α and for d equal to 20mm three samples have been tested, while for the other two values of the bolt diameter only two specimens have been analysed.

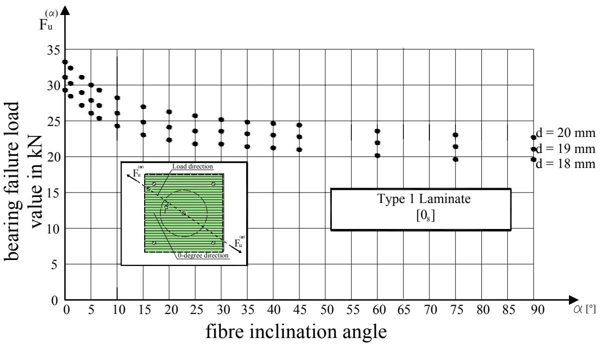

Fig. 6: Type 1 laminate: Curve of $F_u^{(\alpha)}$ in function of the angle α for each bolt diameter *d*.

As observed from the plots, for all the examined values of bolt diameter the pin-bearing load failure notably decreases in the interval of the angle α between 0° and 10° (reduction of 16%).
In the interval 10°<α<90° the pin-bearing failure load curve is characterised by a less accentuated inclination in relation to the initial part (0°<α<10°) and, as expected, it gives the lowest value in correspondence to angle α equal to 90° (sample P15 – Tab. 3).
For what concern the bolt diameter effect, fig. 7 shows that the pin-bearing failure load decreases as the bolt diameter decreases.
Tables 3 and 4 summarize the obtained experimental results. In particular table 3 is relative to all ultimate pin-bearing loads for all specimens tested, while table 4 concerns mean values and standard deviations of the aforementioned loads.

Table 3. Values of the pin-bearing failure load for all samples tested : type 1 laminate.

Bolt diameter d [mm]		20			19		18	
Sample	α±0.2	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$	$F_{u,3}^{(\alpha)}$	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$
	[°]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
0 (P0)	0	33.22	32.92	33.52	30.80	31.20	29.05	28.86
1 (P1)	1	32.60	32.44	32.94	30.25	30.15	28.25	28.65
2 (P2)	3	32.76	30.24	31.74	29.40	29.20	27.65	27.37
3 (P3)	5	31.13	30.07	30.12	28.00	28.20	26.50	26.81
4 (P4)	7	29.90	29.90	27.71	27.00	27.20	26.05	25.73
5 (P5)	10	28.22	29.13	25.90	26.55	26.05	24.75	25.05
6 (P6)	15	25.72	28.01	26.73	25.05	25.19	23.50	23.74
7 (P7)	20	25.92	27.52	25.22	23.85	24.15	22.90	22.57
8 (P8)	25	26.46	26.46	24.00	23.90	23.50	22.00	22.32
9 (P9)	30	25.20	26.42	25.33	23.20	23.58	22.00	21.60
10 (P10)	35	24.67	25.96	23.92	23.10	22.90	21.40	21.75
11 (P11)	40	24.01	25.40	24.51	23.00	22.60	21.55	21.27
12 (P12)	45	24.57	23.82	24.93	22.30	22.70	21.35	21.16
13 (P13)	60	23.62	23.63	23.55	22.00	22.40	20.50	20.73
14 (P14)	75	22.99	23.00	23.19	21.75	21.45	19.70	20.07
15 (P15)	90	22.68	22.42	22.76	21.50	21.10	19.80	19.52

Table 4. Mean values of the pin-bearing failure load for type 1 laminate.

Bolt diameter d [mm]		20		19		18	
Sample	α±0.2	$F_{u,\,mean}^{(\alpha)}$	St. Dev.	$F_{u,\,mean}^{(\alpha)}$	St. Dev.	$F_{u,\,mean}^{(\alpha)}$	St. Dev.
	[°]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
0 (P0)	0	33.28	0.0468	31.00	0.0186	29.28	0.0800
1 (P1)	1	32.58	0.0172	30.20	0.0791	28.50	0.0050
2 (P2)	3	31.38	0.0972	29.30	0.0405	27.38	0.0200
3 (P3)	5	30.03	0.0133	28.10	0.0486	26.50	0.0200
4 (P4)	7	29.17	0.0433	27.10	0.0505	25.40	0.0200
5 (P5)	10	28.15	0.0948	26.30	0.0441	24.45	0.1250
6 (P6)	15	27.01	0.0813	25.12	0.0286	23.55	0.0096
7 (P7)	20	26.22	0.0841	24.00	0.0529	22.90	0.0450
8 (P8)	25	25.64	0.0075	23.70	0.0521	22.30	0.0800
9 (P9)	30	25.15	0.0616	23.39	0.0791	21.85	0.0718
10 (P10)	35	24.82	0.0886	23.00	0.0604	21.50	0.0200
11 (P11)	40	24.62	0.0220	22.80	0.0394	21.30	0.0800
12 (P12)	45	24.43	0.0283	22.50	0.0177	21.00	0.0800
13 (P13)	60	23.60	0.0019	22.20	0.0268	20.50	0.0800
14 (P14)	75	23.03	0.0127	21.60	0.0697	20.00	0.0450
15 (P15)	90	22.60	0.0316	21.30	0.0381	19.60	0.0800

Table 5. Reduction of the pin-bearing failure load varying the bolt diameter d.

Sample	α±0.2	$1-F_u^{(\alpha)}(19)/F_u^{(\alpha)}(20)$	$1-F_u^{(\alpha)}(18)/F_u^{(\alpha)}(20)$
	[°]	[%]	[%]
0 (P0)	0	6.9	12.0
1 (P1)	1	7.3	12.5
2 (P2)	3	6.6	12.7
3 (P3)	5	6.4	11.8
4 (P4)	7	7.1	12.9
5 (P5)	10	6.6	13.1
6 (P6)	15	7.0	12.8
7 (P7)	20	8.5	12.7
8 (P8)	25	7.6	13.0
9 (P9)	30	7.0	13.1
10 (P10)	35	7.3	13.4
11 (P11)	40	7.4	13.5
12 (P12)	45	7.9	14.0
13 (P13)	60	5.9	13.1
14 (P14)	75	6.2	13.2
15 (P15)	90	5.8	13.3
mean value		**7.0**	**13.0**
standard deviation		**0.55**	**0.71**

Is then possible to assume that the pin-bearing failure load depends linearly on the diameter d. The average percentage reductions of the aforementioned load for the diameters 18 and 19mm, as reported in table 5, with respect to the value obtained for bolt diameter 20mm, are equal to 13% and 7% less, respectively. These reductions are similar to the corresponding bolt diameters reductions (10% and 5% respectively). Only for unidirectional laminates, it is possible to convert the present results, given in terms of bearing failure, in bearing strength as in the classical formula used for steel.

Type 2 and 3 Laminates:

Figure 8 shows the curves of $F_u^{(\alpha)}$ varying the angle α and the bolt diameter (*d*) for type 2 laminate. It is worth noting that the curves have been obtained using the average values. In particular, for each value of angle α and bolt diameter two samples have been tested. It is possible to observe that the three curves present a symmetrical trend with respect to the minimum value obtained for α=45°.
As already obtained in [12], in terms of pin-bearing failure load between the two cross-ply laminates there is a difference less than 5%. Then, it can be assumed that pin-bearing capacity is not affected by the stacking sequence and therefore, for the sake of brevity, the complete set of the experimental values for type 3 laminates is not reported here. Confirming the trade shown for type 1 laminate, pin-bearing failure load notably decreases (14%) in the interval of the angle α between 0° and 15°.
In the interval (15°<α<45°) the reduction attains the value of 20% less. For a detailed discussion about the influence of angle α see [12].
Tables 6-8 summarize the results of the experimental investigation for type 2 (and 3) laminates.

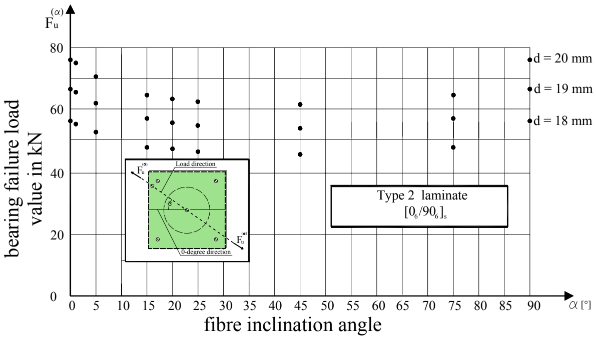

Fig. 6: Type 1 laminate: Curve of $F_u^{(\alpha)}$ in function of the angle α for each bolt diameter *d*.

Table 6. Values of the pin-bearing failure load for all samples tested : type 2 and 3 laminates.

Bolt diameter d [mm]		20		19		18	
Sample	α±0.2	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$	$F_{u,1}^{(\alpha)}$	$F_{u,2}^{(\alpha)}$
	[°]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
0 (P0)	0	76.10	75.78	66.15	65.85	57.10	56.90
1 (P1)	1	74.20	74.60	64.80	65.20	55.90	56.10
2 (P2)	5	70.10	69.90	61.05	60.95	53.15	52.85
3 (P3)	15	64.91	65.09	56.90	56.10	49.50	48.70
4 (P4)	20	63.32	62.68	54.80	55.20	47.80	48.20
5 (P5)	25	61.85	62.15	54.10	53.90	46.95	47.05
6 (P6)	45	60.87	61.13	53.15	52.85	45.55	45.45
7 (P7)	75	65.21	64.79	57.00	57.04	49.30	48.70
8 (P8)	90	76.00	75.88	65.90	66.10	57.20	56.80

Table 7. Mean values of the pin-bearing failure load for type 2 and 3 laminates.

Bolt diameter d [mm]		20		19		18	
Sample	α±0.2	$F_{u,\,mean}^{(\alpha)}$	St. Dev.	$F_{u,\,mean}^{(\alpha)}$	St. Dev.	$F_{u,\,mean}^{(\alpha)}$	St. Dev.
	[°]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
0 (P0)	0	75.94	0.0630	66.00	0.0450	57.00	0.0200
1 (P1)	1	74.40	0.2310	65.00	0.0800	56.00	0.0200
2 (P2)	5	70.00	0.0280	61.00	0.0050	53.00	0.0450
3 (P3)	15	65.00	0.0160	56.50	0.0200	49.10	0.0020
4 (P4)	20	63.00	0.0160	55.00	0.0800	48.00	0.0800
5 (P5)	25	62.00	0.0240	54.00	0.0200	47.00	0.0050
6 (P6)	45	61.00	0.0600	53.00	0.0450	45.50	0.0050
7 (P7)	75	65.00	0.0880	56.60	0.0200	49.00	0.0100
8 (P8)	90	75.94	0.0078	66.00	0.0200	57.00	0.0800

Table 8. Reduction of the pin-bearing failure load varying the diameter d.

Sample	$\alpha \pm 0.2$	$1 - F_u^{(\alpha)}(19) / F_u^{(\alpha)}(20)$	$1 - F_u^{(\alpha)}(18) / F_u^{(\alpha)}(20)$
	[°]	[%]	[%]
0 (P0)	0	13.1	24.9
1 (P1)	1	12.6	24.7
2 (P2)	5	12.9	24.3
3 (P3)	15	12.3	23.7
4 (P4)	20	12.7	23.8
5 (P5)	25	12.9	24.2
6 (P6)	45	13.1	25.4
7 (P7)	75	12.3	23.7
8 (P8)	90	13.1	24.9
mean value		**12.8**	**24.4**
standard deviation		**0.31**	**0.62**

It is confirmed that pin-bearing failure load depends linearly on the bolt diameter d. In particular, when d assumes the value 19mm the average reduction of pin-bearing failure load is about 13% while for d=18mm such reduction attains the value 25%. Despite of the results obtained for unidirectional laminates, in the case of bidirectional ones, these reductions are different from those coming out from the corresponding bolt diameters ones. They depend, as underlined in [6] also, on the number of plies in 0-degree direction. This is the reason why the results are reported in terms of bearing load and not in terms of bearing strength.

5. Conclusions and future developments

The effects of bolt diameter on the pin-bearing failure load of composite bolted joints have been investigated in this experimental study. Three different types of laminates have been tested: one of them is mono-directional while the other two are bi-directional. The results presented have shown a linear reduction of the above failure load varying the bolt diameter for the three types of symmetrical laminates. Finally the authors have proposed a design formula for the prediction of the pin-bearing failure load in function of fibre inclination angle and bolt diameter.

Further developments of this study will include:

- the study of the influence on the bearing load failure of the surface of the rigid washers placed under the bolt-head on both unidirectional and bidirectional FRP elements;
- the analysis of different types of bolted joints characterised by the presence of more rows of bolts in order to evaluate the load distributions coefficients of each row.

6. References

1. Head, P. R. X, *Advanced composites in civil engineering – A critical overview at this high interest, low use stage of development*. Second international conference on advanced composite materials in bridges and structures, Montréal, Québec, Canada, 3-15, 1996.
2. Turvey, G.J. and Cooper, C., Review of tests on bolted joints between pultruded GRP Profiles. Proceedings of the Institution of Civil Engineers, Structures & Buildings, vol. 157, 211-233, (2004).
3. Clark, J. L., *Structural Design of Polymer* Composites – EUROCOMP Design Code and Handbook, S & F Spon, (1996).
4. Kelly, G., Hallström, S., Pin-bearing strength of carbon fibre/epoxy laminates: effects of bolt-hole clearance. Composites Part B: Engineering, Vol. 35, 331-343, (2004).
5. Counts W.A., and Johnson W.S., Bolt pin-bearing fatigue of polymer matrix composites at elevated temperature. Int. Journal of fatigue, Vol. 24, 197-204, (2002).
6. Xiao, Y., Ishikawa, T., Bearing strength and failure behaviour of bolted composite joints (part I: experimental investigation). Composites Science and Technology: Engineering, Vol. 65, 1022-1031, (2005).
7. Xiao, Y., Ishikawa, T., Bearing strength and failure behaviour of bolted composite joints (part II: modelling and simulation). Composites Science and Technology: Engineering, Vol. 65, 1032-1043, (2005).
8. Vangrimde, B., Boukhili, R., Pin-bearing stiffness of glass fibre-reinforced polyester: influence of coupon geometry and laminate properties. Composite Structures, vol. 58, 57-73, (2002).
9. Vangrimde, B., Boukhili, R., Descriptive relationships between pin-bearing response and macroscopic damage in GFRP bolted joints. Composites Part B: Engineering, Vol. 34 (8), 593-605, (2003).
10. Vangrimde, B., Boukhili, R., Analysis of the pin-bearing response test for polymer matrix composite laminates: pin-bearing stiffness measurements and simulation. Composite Structures, Vol. 56, 359-374, (2002).
11. Li, R., Kelly, D., and Crosky, A., Strength improvement by fibre steering around a pin loaded hole. Composite Structures, Vol. 57, 337-383, (2002).
12. Ascione F., Feo L., Maceri F., An experimental investigation on the pin-bearing failure load of glass fibre/epoxy laminates. Composites Part B: Engineering, Vol. 40, 197-205, (2009).
13. Barbero E. J., *Introduction to Composite Materials Design,* Taylor & Francis, (1998).