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Moment-rotation response of nominally pinned beam-to-column joints for frames of pultruded fibre reinforced polymer

Jawed Qureshi [a,*], J. Toby Mottram [b,1]

[a] School of Architecture, Computing and Engineering (ACE), University of East London, 4-6 University Way, Beckton, London E16 2RD, United Kingdom
[b] Civil Research Group, School of Engineering, The University of Warwick, Coventry CV4 7AL, United Kingdom

HIGHLIGHTS

- Moment-rotation behaviour of pinned joints in pultruded frames is characterised.
- Joint stiffness is more variable than moment resistance.
- Both initial stiffness and moment classify the joints as nominally pinned.
- A single specimen measurement of stiffness is unsuitable for use in frame analysis.
- FRP web cleats can crack before the mid-span deflection of a beam exceeds span/340.

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ABSTRACT

This paper presents the test results to characterise the moment-rotation response of nominally pinned joints in frames of pultruded shapes. Mimicking conventional steel construction the major-axis beam-to-column joints are formed using pultruded FRP web cleats having steel bolting. There are two joint configurations with either a single row of three or two bolts per cleat leg. Testing is conducted on nominally identical specimens to statistically quantify the key joint properties. The average stiffness of all joints at damage onset is found to be 50% more variable than the average moment resistance. The presence of 70% difference between the minimum and maximum initial stiffness measured makes a single specimen measurement for stiffness unsuitable for frame analysis. The initial stiffness of the two joint configurations classifies them to be nominally pinned. No appreciable difference in characteristics for the three and two bolt configurations is found; the middle-bolt is unnecessary as two bolts give same results. The most important finding is that delamination cracks, at the top of the FRP cleats, could initiate before the mid-span vertical deflection of a simply supported beam with uniformly distributed load exceeds span/340.

1. Introduction

Fibre reinforced polymer (FRP) materials have seen significant growth over two decades in structural engineering applications, such as in building and bridge projects [1]. These construction materials have properties that make them attractive in engineering structures [2]; they are relatively strong, lightweight, and offer electromagnetic transparency, and durability and corrosion resistance [1–5]. A factor preventing the construction industry from using pultruded construction more widely has been lack of agreed design guidelines, and less knowledge and less confidence with using FRPs instead of traditional construction materials [1].

Standard pultruded shapes mimic their counterparts in structural steelwork and are made by the pultrusion process [1]. They consist of E-glass fibre reinforcement (layers of unidirectional rovings and continuous mats) in a thermoset (e.g. polyester or vinylester) resin based matrix. Pultruded FRP has a density about one quarter of steel [3–5]. Longitudinal tensile strength can be over 200 N/mm^2 and this is comparable with structural steel. The longitudinal modulus of elasticity, at 20 to 30 kN/mm^2, is up to 10 times lower, whereas the modulus of elasticity perpendicular to the direction of pultrusion is one-quarter to one-third of the longitudinal value [3–5]. Due to low modulus the role of a deflection limit is the key to the design of beams.

This paper relates to simple braced frames with simple shear connections between beams and columns, and columns and bases.

* Corresponding author. Tel.: +44 (0) 20 8223 2363; fax: +44 (0) 20 8223 2963.
E-mail addresses: J.Qureshi@uel.ac.uk (J. Qureshi), J.T.Mottram@warwick.ac.uk (J.T. Mottram).
1 Tel.: +44 (0) 24 76 522 528; fax: +44 (0) 24 76 418 922.

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To transfer lateral loading to the ground vertical bracing is required. Joint detailing in Figs. 1–5 uses steel bolting and corresponds to the engineering drawings in [4]. Justification for not permitting adhesive bonding as a method of connection is lack of understanding of its behaviour [5], its unsuitability for connecting steel-shaped FRP components [6–8], and a desire to offer design guidelines for frames that are demountable for reuse and recycling.

The traditional approach in steel construction is to assume frame joint behaviour as either nominally pinned or fully-rigid. In reality, all joints have a moment-rotation (M-ϕ) characteristic that lies between these two 'theoretical' extremes, and this introduces semi-rigid action into the structural engineering considerations [9]. In the absence of numerical and theoretical methods, a joint's M-ϕ curve is determined by full-size laboratory testing [10–14]. Turvey and Cooper [6] reviewed the results of 59 individual tests to determine the M-ϕ characteristics of details for pinned and semi-rigid joint properties. They [6] found that only two pairs of the 59 joints were nominally identical. These authors suggested more testing on nominally identical specimens using identical test set-ups. This issue is addressed by evaluating the results presented later.

The rotational stiffness of beam end connections can be utilised to quantify the increase in load carrying capacity of beams. Turvey [15] developed closed-form equations for vertical deflection, which are functions of initial rotational stiffness, S_i. Values for S_i were determined from the gradients of M-ϕ curves reported in references [8,11–13]. Because none of the tests from the 1990s had more than one batch of two identical specimens the variability in joint stiffness was not adequately accounted for. Simple pultruded joints can be expected to possess a relatively low initial rotational stiffness that is unlikely to make a major contribution to increasing load capacity in beams.

It will be instructive to summarise previous experimental studies with web-cleated joints. Bank et al. [10] reported the first M-ϕ test results. They used 203 mm deep shapes with 152 mm pultruded leg-angle cleats. Mottram [8] proposed ten recommendations based on characterising web-cleated joints with 203 deep shapes and no gap between beam-end and column flange. The authors concluded that adhesive bonding alone cannot be used to connect cleats to frame members, and to increase joint rotation at damage onset, there should be a gap of 6 to 12 mm between a beam-end and column face. In another test series, Mottram and Zheng [16] tested simple joints with 254 mm deep WF shapes and including the gap of 10 mm. They concluded that the ten recommendations in [8] were applicable to the joints with 254 mm deep profiles.

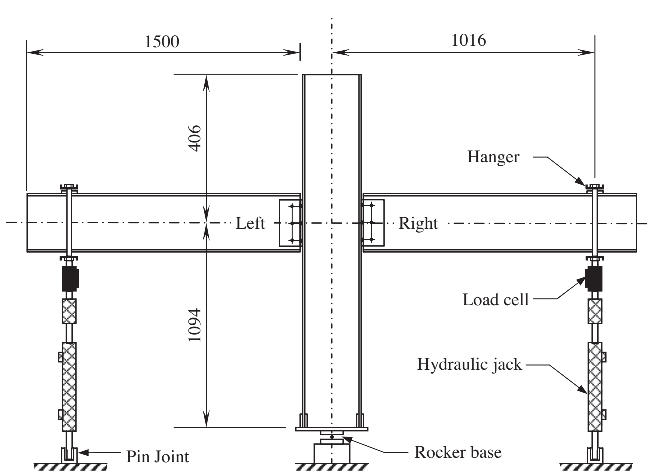

Fig. 1. Cruciform test configuration (all dimensions are in mm).

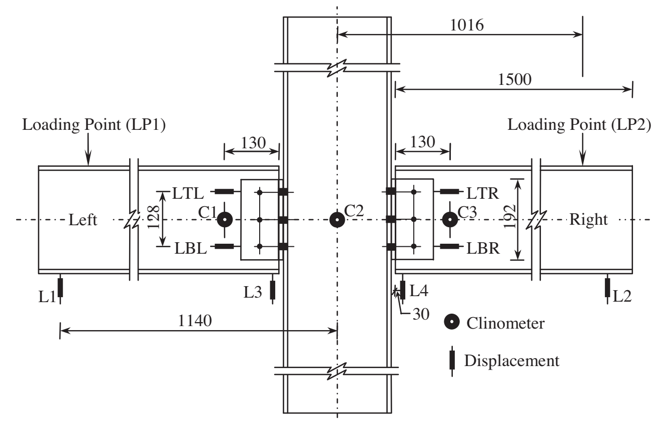

Fig. 2. Location of instrumentation in nominally pinned beam-to-column joint tests (all dimensions are in mm).

Additional individual tests with web-cleated joints are reported by Turvey and Cooper [18,19] and Turvey [20]. None of the joint details examined had a batch with more than two nominally identical joints.

The aim of this paper is to characterise the key joint properties by testing nominally identical joints under identical test conditions. Specimen repetition ensures that variations in the test results are taken into account. Presented will be data from 16 major-axis joints with web cleats (10 with three bolts per cleat and six for the two-bolt case). Moment-rotation behaviour, failure modes and joint properties are obtained and analysed. This research helps to bridge the gaps in knowledge and understanding [21] of overall structural response of simple beam-to-column joints of FRP profiles.

2. Test configuration and test procedure

Figs. 1–5 show a major-axis beam-to-column joint connected to a central column through a pair of web cleats. The experimental set-up follows [8,9,16] with end vertical loading applied to two back-to-back cantilever beams. Each specimen therefore has two nominally identical joints. The beam and column of 1500 mm length comprise WF section of size 254 × 254 × 9.53 mm from Pultex® SuperStructural 1525 series of Creative Pultrusions [3]. Web cleats, of height 192 mm, are cut from an equal leg-angle of size 100 × 100 × 9.53 mm [3]. The cleats have their unidirectional roving reinforcement parallel to the direction of the shear force.

The longitudinal centreline of the beams is set at a vertical distance of 1094 mm from the base of the column. This height is dictated by the dimensions of hydraulic jacks and base fixtures. The bottom end of the column is placed on a steel rocker base fixture, which allows 'free' in-plane rotation (in the plane of Fig. 1) to justify the assumption of a pinned base. The reason for using a pinned column base is to make sure that both Left and Right beams are subjected to the same load.

2.1. Loading procedure and instrumentation

Load is applied through a hanger assembly and a ball bearing (12.7 mm) placed in a hemi-spherical socket at the centre of a steel loading plate illustrated in Fig. 1. This arrangement ensures vertical alignment of the load with minimal axial force components. Loading is applied at distances of 1016 mm from the column's centreline. The distance of 1016 mm is dictated by the layout of the anchor points on the strong floor, which are spaced at 406 mm centres. The applied force is measured by two tension load cells, each

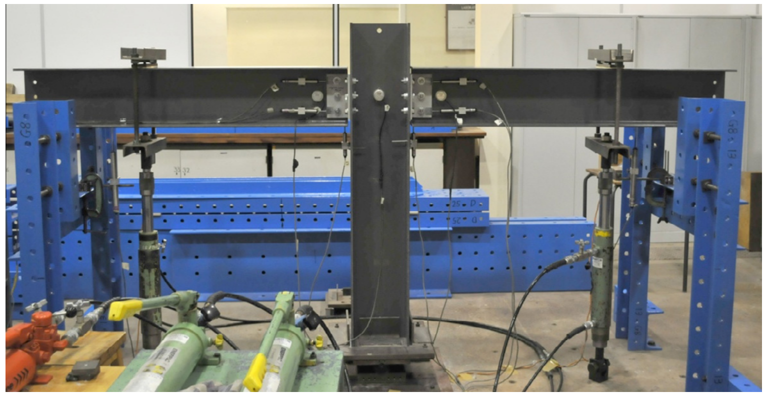

Fig. 3. General test arrangement for beam-to-column joints.

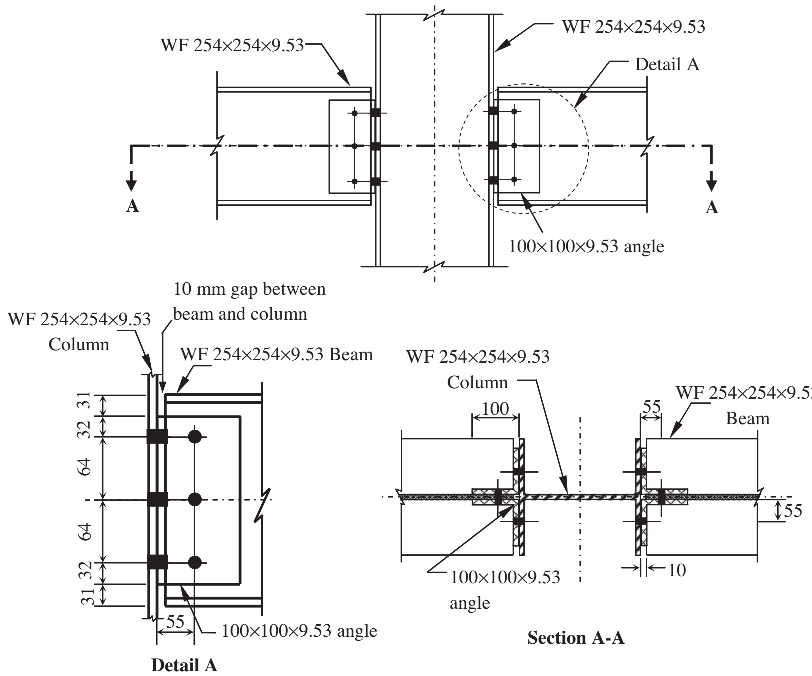

Fig. 4. Connection details for nominally pinned beam-to-column joint tests (all dimensions are in mm).

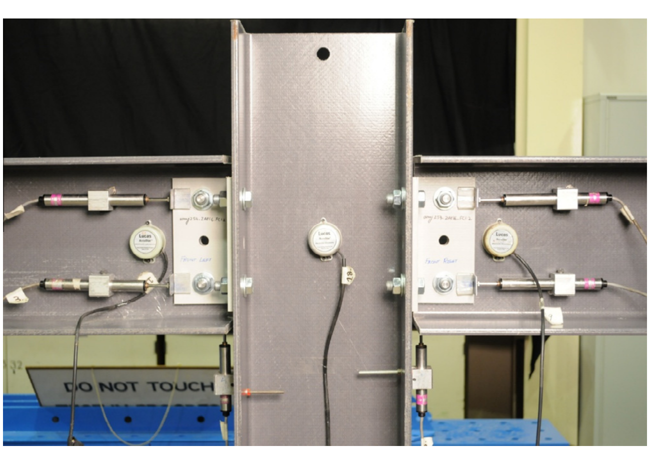

Fig. 5. Details of beam-to-column joint test Wmj254_2M16_FC.

of 9 kN capacity, to a resolution of ±0.01 kN. Each specimen is statically loaded such that both (Left and Right) joints experience rotation increments of about 2 mrad. This procedure is continued until a delamination failure is observed at the top of web cleats. After this damage onset, the rotation increment is increased to 5 mrad until one of the joints rotates without moment increase.

The extent of permanent deformation and change in joint rotational stiffness (S) are determined by unloading and reloading after rotation ϕ was above 12.8 mrad. S reported in the paper is for the secant stiffness. Justification for choosing 12.8 mrad is that it is an end rotation for a simply supported beam with uniformly distributed load having a central deflection (w_c) of $L/250$, which is a deflection limit for general public access flooring given in [17]. Testing continues until either joint resistance reduces or excessive rotation could endanger specimen stability.

Locations of the instrumentation are shown in Figs. 2 and 3 shows a specimen under test. In the specimen labelling scheme, L is for Left-side and R for Right-side in a pair of joints. Rotations and displacements are measured, at each increment and after a time lapse of five minutes, using clinometers and strain gauge based displacement transducers. Rotations are recorded to a resolution of 0.02 mrad (linear to ±1% over a 10° range) and axial displacements to ±0.01 mm. The Left and Right rotation is measured by, respectively, clinometers C1 and C3. They are placed on the longitudinal axis of a beam and 130 mm from the end adjacent to the column flange. The verticality of the column is measured by C2, which is located at the intersection of the centroidal axes of the beam and column members. The difference between beam and column rotations (i.e., C1–C2 and C3–C2) gives ϕ.

Relative slip between a pair of web cleats and the beam is measured by four displacement transducers, designated in Fig. 2 as LTL, LBL, LTR and LBR. The first letter, L, in label LTL denotes there is a vertical separation between the two horizontal transducers, and second and third letters denote Top bolt on Left-side of the specimen. The displacement transducers L1 and L2 measure the vertical deflection of the beam at the loaded ends. While L3 and L4 measure vertical slip at the joints on the Left and Right sides.

Slip rotation has to be subtracted from the measured rotation, to obtain ϕ that is due to the prying action. To calculate the slip rotation, ϕ_{slip}, we used the displacements measured by the two transducers (e.g. LTL and LBL in Fig. 2) placed on web cleats near top and bottom bolts (see Fig. 5). To determine ϕ_{slip} the following geometric relationship is used:

$$\phi_{slip} = \tan^{-1}\left(\frac{lb - lt}{l}\right) \times 1000 \qquad (\text{mrad}) \tag{1}$$

where lt and lb are the horizontal slip measured by the LT and LB pair of displacement transducers and l is the vertical separation of 128 mm between the centrelines of top and bottom bolts. Slip rotation determined from Eq. (1) is subtracted from the measured rotation to obtain the results reported in Section 3.

2.2. Connection detailing

Fig. 4 shows connection details, prepared in accordance with drawings in the Strongwell Design Manual [4] and clauses in an ASCE Pre-Standard [24]. Bolting is standard size steel bolts of M16 grade 8.8 with standard ϕ 35 mm by 3 mm thick steel washers. The portion of bolt shaft bearing onto FRP material is unthreaded. Bolts are tightened to the snug-tight condition, achieved by tightening the bolt to full effort of a worker using a hand operated wrench [27]. This level of bolt tightening is achieved as per guidance for the snug-tight condition in [28–29].

In the test series there is one important deviation from the detailing in [4,24], the M16 steel bolts make a nearly 'tight-fit' with the pultruded beams. The justification for this change from a 1.6 mm clearance hole size is as follows. In previous work Mottram and Zheng [16] observed the slip rotation as high as 22 mrad due having a hole clearance. Clearly, this slip rotation has to be subtracted from the measured ϕ to establish the actual rotation due to the prying action. In practise the magnitude of the available slip rotation will depend on how cleat connections are assembled. One extreme situation can be when the relative displacement between top and bottom bolt levels and the beam web and the cleat pair is, in opposite directions, 1.6 mm. Assuming lt equal to −1.6 mm and lb equal to +1.6 mm Eq. (1) gives a maximum slip rotation of 25 mrad. The other extreme scenario is when bolts are exactly positioned in the holes such that, before bearing, no horizontal slip can occur at top and bottom bolt levels (i.e. $lt = lb = 0.0$ mm). While, slip rotation has a beneficial effect of increasing ϕ before damage onset, it cannot be relied upon in design because it might not be available. The no slip condition has been evaluated in this study because it poses the worst practical design situation that needs to be considered when preparing clauses for the simple joints of pultruded FRP material.

To achieve almost tight-fitting bolting a CNC drilling machine was used for precision hole positioning and size. In beams the diameter is 16 mm, while for ease in assembling, holes in column flanges are 17 mm diameter for a 1 mm clearance. The larger sized holes in the column did not affect the joint's M-ϕ response because slippage for these connections is in the vertical plane. Despite the tight-fitting bolts on the beam side there was limited slip rotation because of the variable diameters in off-the-shelf M16 bolts, which were measured as 15.6 to 15.9 mm. For the worst case scenario, when the web cleat displaces in opposite directions, the maximum ϕ_{slip} could be 6.5 mrad.

2.3. Joint configuration

This test series consists of two joint configurations [4] with a single row of either three or two bolts per cleat leg. To form the two-bolt configuration the central bolt in Fig. 4 was removed (see Fig. 5). Joints having three bolts are denoted by Wmj254_3M16_FC and having two bolts by Wmj254_2M16_FC. Labelling is for a *254* × 254 × 9.53 mm web-cleated beam and ma*j*or axis column, with a single row of 3 *M16* or 2 *M16* bolts in a FRP web cleat. All other test conditions are the same for the two- and three-bolted configurations.

3. Results and discussion

The most important feature is that the joint characterisation is conducted with more than one pair of nominally identical joints. Previously, similar testing [8,11–13,16,18–20] has been used to characterise a batch comprising of only a nominally identical pairs of joints. For Wmj254_3M16_FC five specimens (10 joints) are characterised and with Wmj254_2M16_FC, after finding that the test results with two bolts are similar to three bolts, the number of specimens is three (six joints).

3.1. Joint properties

Measured joint properties are given in Tables 1 and 2, after ϕ_{slip} is compensated for. For clarity the minimum and maximum batch values per property are highlighted in bold. In the tables column (1) gives the specimen labelling. Initial joint properties, when the M-ϕ response is linear, are given in columns (2) to (4), and are represented by initial moment (M_i), initial rotation (ϕ_i) and initial stiffness ($S_i = M_i/\phi_i$). Similarly, the damage onset properties, when material failure is first observed, are given by M_j, ϕ_j and $S_j = (M_j/\phi_j)$ in columns (5) to (7). Column (8) presents the maximum moment, M_{max}, and corresponding maximum rotation, ϕ_{max}, is reported in column (9). The Mean and Coefficient of Variation (CV) of each property are given in the bottom two rows of the tables.

For all 16 specimens the mean M_j is about 1 kNm, and the CV < 10%. From column (8) the average M_{max} for three- and two-bolted configuration is 1.86 and 1.76 kNm, with CV < 7%, which shows that the moment resistance does not vary much within, and between the two batches. What does have significant variation is the mean ϕ_{max} with a range of 30 to 69 mrad. CVs in S_i are 17% and 7% for three- and two-bolts. The higher variation in initial stiffness only exists in the linear elastic range of M-ϕ, when damage in web cleats is absent. To support this finding we observed that the CVs for S_j are similar, at 11% and 10% for the three- and two-bolt configurations. One finding from testing more than two joints per detailing is that stiffness is more variable than moment.

One objective of testing was to establish that joint properties with three- or two-bolts would be approximately the same. Because they are, a second key finding is that the third bolt is not required. The first step in developing good working practise

Table 1
Joint properties for beam-to-column joint tests Wmj254_3M16_FC (compensated for slip).

Specimen label (1)	M_i (kN m) (2)	ϕ_i (mrad) (3)	$S_i = M_i/\phi_i$ (kN m/rad) (4)	M_j (kN m) (5)	ϕ_j (mrad) (6)	$S_j = M_j/\phi_j$ (kN m/rad) (7)	M_{max} (kN m) (8)	ϕ_{max} (mrad) (9)
Wmj254_3M16_FC1.1 (Left)	0.52	4.8	108	1.02	13.3	76	1.77	**69**
Wmj254_3M16_FC1.1 (Right)	0.48	5.1	**94**	1.07	**16.2**	**66**	1.83	53
Wmj254_3M16_FC1.2 (Left)	0.49	3.9	126	1.03	12.9	80	1.96	34
Wmj254_3M16_FC1.2 (Right)	0.51	3.2	**161**	1.04	10.4	**100**	1.97	40
Wmj254_3M16_FC1.3 (Left)	0.48	3.5	137	1.13	13.5	83	1.92	36
Wmj254_3M16_FC1.3 (Right)	0.49	3.4	142	1.13	12.5	90	1.93	44
Wmj254_3M16_FC1.4 (Left)	0.49	4.8	102	1.06	12.7	84	1.82	**31**
Wmj254_3M16_FC1.4 (Right)	0.52	4.3	121	1.08	12.7	85	1.84	31
Wmj254_3M16_FC1.5 (Left)	0.45	4.2	107	0.87	**9.7**	89	1.77	34
Wmj254_3M16_FC1.5 (Right)	0.45	4.1	110	0.91	9.7	94	1.80	32
Mean of 10	0.49	4.1	121	1.03	12.4	85	1.86	40
CV	5.1%	16%	17%	8.2%	16%	11%	4.1%	30%

Table 2
Joint properties for beam-to-column joint tests Wmj254_2M16_FC (compensated for slip).

Specimen label (1)	M_i (kN m) (2)	ϕ_i (mrad) (3)	$S_i = M_i/\phi_i$ (kN m/rad) (4)	M_j (kN m) (5)	ϕ_j (mrad) (6)	$S_j = M_j/\phi_j$ (kN m/rad) (7)	M_{max} (kN m) (8)	ϕ_{max} (mrad) (9)
Wmj254_2M16_FC1.1 (Left)	0.23	1.7	139	0.97	17.0	57	1.89	48
Wmj254_2M16_FC1.1 (Right)	0.23	1.5	**153**	1.01	15.1	67	1.91	47
Wmj254_2M16_FC1.2 (Left)	0.27	1.9	142	1.00	13.1	**76**	1.75	37
Wmj254_2M16_FC1.2 (Right)	0.26	1.9	137	1.03	14.7	70	1.78	61
Wmj254_2M16_FC1.3 (Left)	0.25	2.0	**125**	0.94	13.7	69	1.60	**64**
Wmj254_2M16_FC1.3 (Right)	0.25	1.8	143	0.97	**12.9**	75	1.62	**30**
Mean of 6	0.25	1.8	140	0.99	14.4	69	1.76	48
CV	6.5%	10%	7%	3.3%	11%	10%	7.3%	27%

can be for Strongwell [4] to remove drawings for joints requiring three bolts per cleat leg.

3.2. Moment-rotation curves

M-ϕ curves for specimens Wmj254_3M16_FC1.5 and Wmj254_2M16_FC1.2, with rotation slip, are presented in Figs. 6 and 7. Plotted in Figs. 8 and 9 are the same results after ϕ_{slip} has been removed. The Left-side is given by the solid line curve and the Right-side by the dashed line curve. M and ϕ values at damage onset are represented in the figures by the solid circle symbols. When two joint values are given in the following discussion the first is for the Left-side and the second for the Right-side.

For Wmj254_3M16_FC1.5 the slip rotations at damage onset are 6 and 0.8 mrad. Because this bolt slippage is present, the two M-ϕ curves in Fig. 6 are quite different in shape, and ϕ_j is 15.7 and 10.5 mrad. This compares with 9.7 mrad (for both joints) in Fig. 8 when ϕ_{slip} is accounted for. When slippage is involved, the curves in Fig. 6 give the impression that the Left joint has a nonlinear response from a low M of 0.25 kNm. Because there was no delamination damage at this moment the nonlinearity is seen to be solely due to slip rotation. When ϕ_{slip} is removed, the M-ϕ response of both joint sides is found to be equivalent, until the onset of FRP failure at ϕ_j.

The existence of ϕ_{slip} in Wmj254_2M16_FC1.2. (Fig. 7) increases ϕ_j to 15.2 and 18 mrad. Following slip compensation, the pair of ϕ_js are lower at 13.1 and 14.7 mrad (Fig. 9). This behaviour might lead the misinformed to misinterpret ϕ_j that can be used when establishing a design limit for central deflection (w_c) of a simply supported beam with a uniformly distributed load. The saw-tooth shape of the curves in Figs. 6–9 is due to M-ϕ readings being taken immediately after load application and after a lapse of five minutes. The drop in M indicates that the web cleats experienced creep relaxation and, later, also progressive damage.

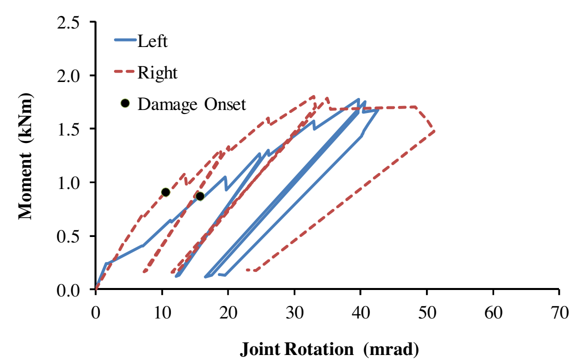

Fig. 6. Moment-rotation curves for Wmj254_3M16_FC1.5 (with slip rotation).

In Fig. 8 the response for the three-bolt configuration remains, approximately, linear elastic until the cleats start to delaminate. The M-ϕ curves become non-linear for moment >0.5 kNm and the damage started when ϕ_j is 9.7 mrad. To assess the extent of stiffness reduction, specimen Wmj254_3M16_FC1.5 was unloaded and reloaded after there was material damage. The results of these stages in testing are shown in Fig. 8.

Tables 1 and 2 indicate that M-ϕ characteristics for two- and three-bolts are (very) similar. The discussion to follow is for the two-bolted configuration. The moment-rotation curves for Wmj254_2M16_FC1.2 in Fig. 9 show both linear elastic and non-linear responses. Linearity is found for M to only 0.27 kNm, which is half of what is observed with three bolts. Most importantly, M_j at 1 kNm is the same for both three- and two-bolted cleats.

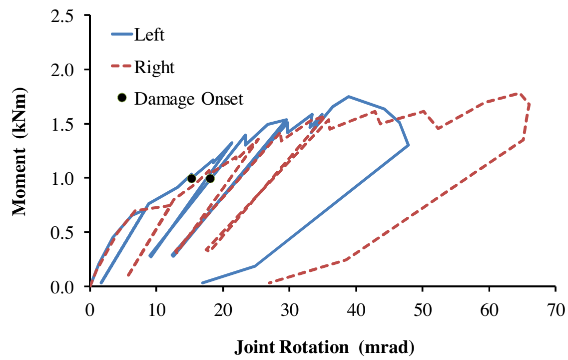

Fig. 7. Moment-rotation curves for Wmj254_2M16_FC1.2 (with slip rotation).

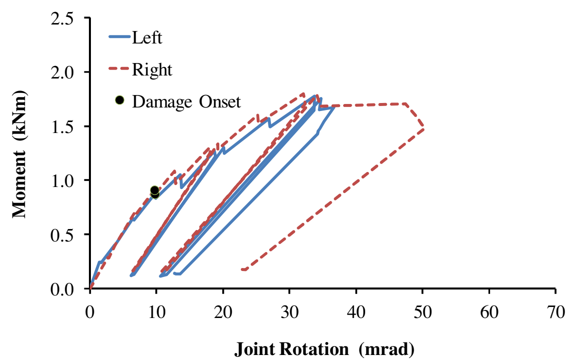

Fig. 8. Moment-rotation curves for Wmj254_3M16_FC1.5 (compensated for slip).

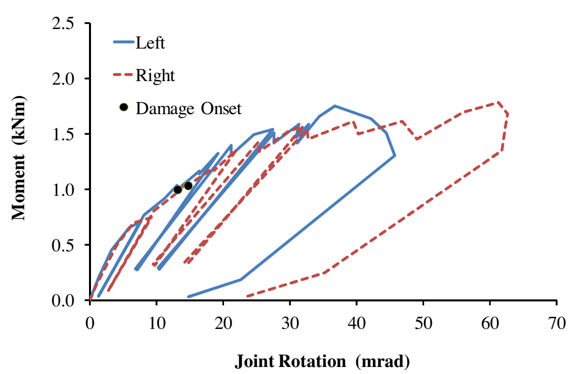

Fig. 9. Moment-rotation curves for Wmj254_2M16_FC1.2 (compensated for slip).

3.3. Failure modes

All 16 joints (for eight (Left and Right) specimens) ultimately failed due to extensive delamination damage at the top of web cleats and near the fillet radius, as shown in Figs. 10 and 11. Audible acoustic emission provided the first evidence of the hairline (delamination) cracks seen in Fig. 10. These cracks are found to run along an interface between a layer of mat and unidirectional roving reinforcement. Fig. 10 shows that, through the leg-angle thickness, these layers are not at constant positions, and this test variability partially explains the variation in the rotation results (ϕ_i, ϕ_j and ϕ_{max}) reported in Tables 1 and 2. After hairline cracks appeared, application of further deformation widens and lengthens them, and created new visible surface cracks. Because extensive damage reduced the moment capacity, one joint side would rotate more than the other, as seen in Fig. 12.

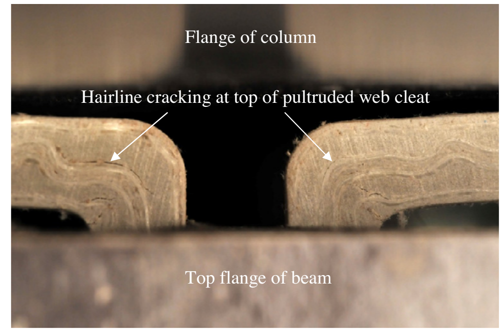

Fig. 10. Close-up of damage onset near the fillet radius of a pair of web cleats in specimen Wmj254_3M16_FC1.5 (viewed from above).

3.4. Serviceability rotation limit

Eurocode 3 for design of steel structures [22] specifies serviceability limits for deflections of beams. In the UK [22] the limit in steel buildings for vertical deflection (w_c) for beams carrying plaster or other brittle finish is $L/360$ and for other beams it is $L/200$. From the Eurocode 5 [23] these limits for timber beams are $L/250$ and $L/150$, respectively. Creative Pultrusions Inc. [3] and Strongwell [4] have tabulated load tables for 8 m span beams with a maximum w_c of $L/180$ and $L/100$, respectively. These Design Manual values [3–4] are not specified by the two pultruders to be used as serviceability limit state deflection limits.

The required (serviceability) rotation, for a simply supported beam subjected to a uniformly distributed load, is 12.8, 21 or 32 mrad for a w_c of $L/250$, $L/150$ or $L/100$, respectively. Comparing these 'theoretical' rotations with the measured ϕ_js in Tables 1 and 2 shows that the cleat connections will have delamination cracks before w_c reaches $L/150$. Combining the 16 test ϕ_js the mean ϕ_j at damage onset is 13.1 mrad, and this rotation limit would suggest that the $L/250$ limit is acceptable. Annex D in Eurocode 0 [25] is used to compute a characteristic damage rotation as 9.4 mrad (from Mean − 1.82 × Standard deviation, with the CV unknown). This ϕ_j value corresponds to a relatively low w_c of $L/340$ when web-cleated joints might experience delamination failure. For applications of pultruded FRP frames in chemically aggressive environments, a deflection limit of $L/250$ could be too liberal.

Providing the working environment is not aggressive, a deflection limit on w_c of $L/250$ (for ϕ_j = 12.8 mrad) should be acceptable with the (two-bolted) joint configuration illustrated in Fig. 4. Since pultruded frames are often commissioned because the FRP material is corrosion resistant [1–5], the test results in Tables 1 and 2 suggest that the limit on w_c should be specified at $L/340$ (for ϕ_j = 9.4 mrad). With this limit there would be confidence for an absence of hairline cracks in FRP cleats for simple joints under service loading.

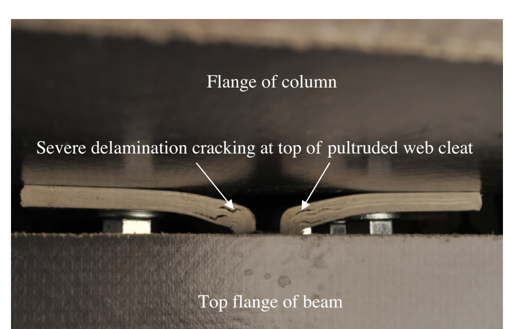

Fig. 11. Ultimate failure of a joint in specimen Wmj254_3M16_FC1.5 (viewed from above).

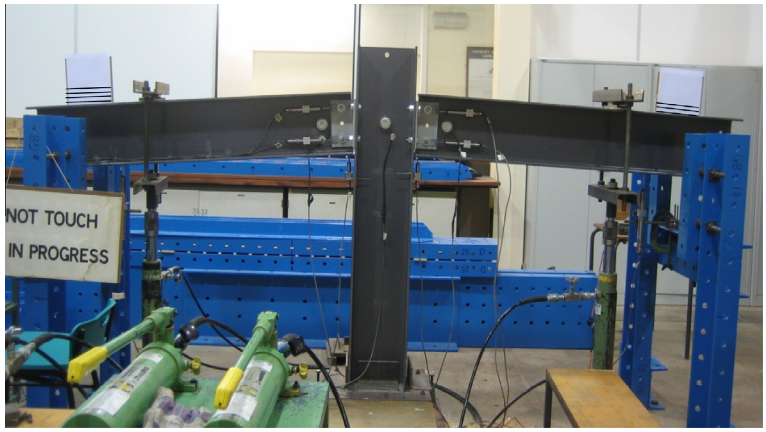

Fig. 12. Excessive joint rotation ($\phi_{max} \geqslant 37$ mrad) post-test with specimen Wmj254_2M16_FC1.2 (results in Table 2).

3.5. Classification of joints

It is useful to know if the rotational stiffnesses for ϕ_i in Tables 1 and 2 are in the range that classifies the joints as nominally pinned. Since classification is independent of the construction material the scheme for steel joints in [26] is acceptable. From Part 1–8 of Eurocode 3 the initial rotational stiffness $S_{j,ini}$, at service loads, is taken as the index property. Here this stiffness measure is taken to be $S_i = (M_i/\phi_i)$ in Tables 1 and 2. If $S_{j,ini}\ L/EI \leqslant 0.5$ [26], with EI/L the flexural stiffness of the beam member, the joint is classified as nominally pinned. If we assume the beam has a span-to-depth of 20 the span (L) is 5.08 m for the 254 mm high (WF) section. Taken from Chapter 3 of [3], the flexural modulus of elasticity (E) of the SuperStructural section is 27.6 kN/mm^2 and the major-axis second moment of area (I) is 8.34×10^7 mm^4. The limit on $S_{j,ini}$ (S_i) for the joint to be classified as nominally pinned is about 230 kNm/rad. Note that if the maximum (practical) span is taken to be 8 m, refer to table for the 254 × 254 × 9.53 mm WF SuperStructural shape in Chapter 4 of [3], the stiffness limit reduces to about 140 kNm/rad. The measured range of S_i reported in column (4) in Tables 1 and 2 is 94 to 161 kNm/rad. A further finding from this study is that the joint detailing in Fig. 4 will classify it as nominally pinned.

4. Concluding remarks

A major contribution to the research reported is that more than one pair of nominally identical joints are used to determine the joint properties for pultruded frames. Test results are reported for a batch of ten joints with three bolts per web cleat leg and for a batch of six joints with two-bolts. Conclusions drawn from analysing the test results are relevant to preparing design guidelines to have safe and reliable web-cleated joints in simple frame construction.

The main findings are:

- Joint moments at loss of linear response, onset of material failure, and ultimate failure do not vary much for the three- and two-bolted configurations. Joints failed due to extensive delamination damage at the top of web cleats that initiated from the fillet radius region.
- The non-constant positioning of the E-glass fibre reinforcing layers thorough the thickness of the leg-angle, especially at the fillet radius region, is seen to have a significant effect on variability of joint rotation at damage onset. This variability in a key joint property needs to be accounted for in guidelines for design standards.
- There is much more batch variation in the secant stiffness with, at damage onset, a variation of 52% and 33% for the three- and two-bolted configurations. It is found that rotational stiffness is more variable than the maximum joint moment (at 23%).
- Because the moment-rotation response for the two-bolt configuration is similar to the three bolted configuration the middle bolt of the three can be removed without any loss or change in structural performance.
- Although previous testing had shown that the joint rotation at damage onset is higher when there is slippage in bolt clearance holes this cannot be relied upon since it depends on where the bolts are positioned with respect to the centres of their holes.
- Providing the working environment is not aggressive, when delamination fracturing at top of pultruded FRP cleats can be tolerated, a serviceability limit state vertical deflection limit of span/250 is acceptable. For aggressive environments, a limit of span/340 is found to be suitable.
- Evaluation of the test results using the classification procedure in Eurocode 3 [26] shows that the joints are classified as nominally pinned.

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