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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.

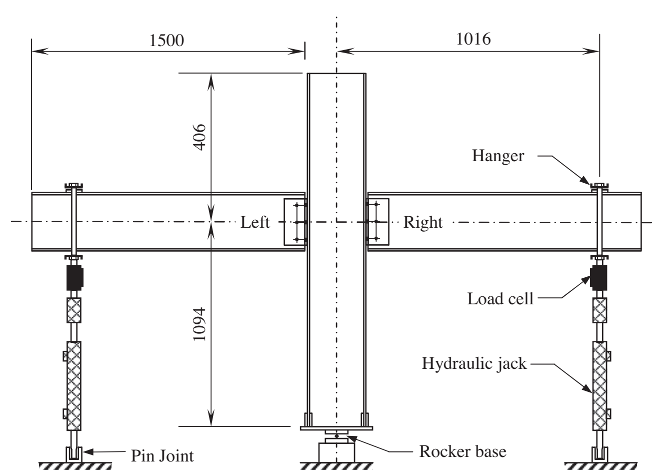

Fig. 1. Cruciform test configuration (all dimensions are in mm).

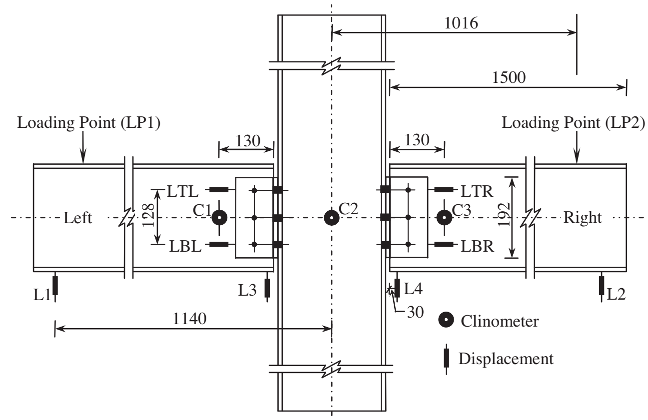

Fig. 2. Location of instrumentation in nominally pinned beam-to-column joint tests (all dimensions are in mm).

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