Beam-to-Beam Eccentric End Plate Connections - Experimental Comparison to Fin Plate and Partial-Depth End Plate Connections

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ABSTRACT

This paper presents a study of eccentric end plate (EEP) beam-to-beam connections as a non-standard detailed design presented in SCI P358 and commonly used for complex geometries where standard simple connections are not suitable. The rotational capacity of EEP connections is often questioned since it should theoretically be a nominally-pinned connection. In this study the rotational behaviour is investigated with a series of moment-rotation experiments and then compared with another two simple connections; a fin plate (FP) connection, and a partial-depth end plate (PDEP) connection. It is concluded that the EEP connection is semi-rigid with a higher stiffness and strength than the FP and PDEP connections which are found to behave as nominally-pinned. The EEP connection imposed higher forces and thus more deformation was obtained on the supporting member in comparison with the FP or PDEP connections. The concluding recommendation is to only use EEP connections if the specific connection design has been verified to be nominally-pinned or by including the fixity in the frame analysis.

1 Introduction

1.1 Overview

Connections play an important role in steel frames. Many structural steel buildings often consist of complex geometries. Therefore, non-standard connection details, such as the eccentric end plate (EEP) connections, fall outside of the standard detail requirements for simple connections. However, there is some concern from the industry that EEP connections may become partially fixed at the ends of a simply supported secondary beam and induce a rotational torsion in the primary beam, thus increasing the stresses in the primary members. It is important to understand the behaviour and classification of the EEP connection so that limitation can be considered in the connection design or the effect can be accounted for in the frame analysis.

This study is focused on an EEP connection with S355 steel fittings, according to SCI P358 (2014); usually used dealing with complex beam geometries and high shear forces. The aim of this study is to determine the behaviour of the EEP connection and compare it to the behaviour of the commonly used fin plate (FP) connections and partial-depth end plate (PDEP) connections. An assessment is made from experimental tests conducted at the University of Leeds with fabricated specimens from Severfield (UK) Ltd. of each of the three connection types.

Extensive literature discusses the behaviour of beam-to-column connections and the effect of their components. However, there is limited work available for beam-to-beam connections, with none available for the EEP connection. The most closely related examples of literature described onwards show the need for more research understanding the behaviour of some complex beam-to-beam connections. Kishi et al. (2005) investigated the rotational behaviour of various end plates on beam-to-column connections and found that end plates which were flush with the flanges (similar to the eccentric end plate studied here), or projected with bolts above and below the beam were considered as semi-rigid or rigid while partial-depth end plates were considered flexible. Sarraj et al. (2007) and Marwan (2007) studied fin plates at ambient and elevated temperatures and found that the initial slipping in fin plates caused rotation. Mensinger and Schwindl (2012) examined beam-to-beam connections but only for long fin plates. Jarrett (1990) also examined fin plates but for beam-to-column connections and concluded that there is noticeable deformation of the column web which is relevant to the current study as it considers a beam web with two different flexible supports. Lema (2009) investigated beam-to-beam connections with bolted end-plates designed for heavy duty steel platforms subjected to seismic loads as well as exceptional loads due to postulated piping ruptures. More recently, da Silva et al. (2012) studied the effect of beam-to-beam structural connections (rigid, semi-rigid and flexible) over the non-linear dynamic behaviour of composite floors when subjected to human rhythmic activities through an extensive parametric finite element (FE) analysis. In 2018, Dowswell discusses new developments in connection design, yet none addressing the EEP connections and their effect on primary beams. Steel Construction (2018) refers that the need for special connections can often be avoided by judicious selection of member sizes and that the top flanges of beams should, where possible, be at a constant level, but this is less critical to cost than eccentric connections.

1.2 Design Method

Standard design practice in the UK suggests adopting the connection details in the SCI P358 (2014). Standardised simple connections, such as fin plates (FP) or partial-depth end plates (PDEP), are provided for standard geometries and are considered nominally-pinned based on previous testing. Non-standard connections, such as the EEP connection, are provided indicatively as a recommendation for complex geometry but cannot be assumed to be nominally-pinned due to lack of testing evidence. The requirement for the classification is dependent on the method of global analysis used, such as:

- Elastic global analysis – classified according to stiffness;
- Rigid-Plastic global analysis – classified according to strength; and
- Elastic-Plastic global analysis – classified according to stiffness and strength.

For stiffness classification, the initial rotational stiffness has to be determined by the moment-rotation relationship, i.e. the relationship of the moment transmitted by the connection, M, and the relative rotational angle of the two members, θ. (Figure 1 in) SCI AD305 (2006) shows the deformation due to the moment-rotation relationship of a beam-to-column connection; the left image of the figure demonstrates that the column and beam centrelines are perpendicular, thus the full moment is transmitted with no additional rotation. On the right image of the figure an additional rotation, θ, is shown between the column and beam centrelines which demonstrates that the connection is more ductile than the left image. The behaviour shown is similar to that of a beam-to-beam connection as well.

The connection behaviours are compared with the classification boundaries given on the moment-rotation curve graph as shown in BS EN 1993-1-8 (2005). Zone 3 indicates the area that a connection can be classified as nominally-pinned and the equation is used in the investigation; this is assumed to be sufficiently ductile for simply supported beams. Zone 1 specifies the region for which a connection provides sufficient moment resistance to be classified as rigid. Zone 2 is the region between Zone 1 and 3 and is classified as semi-rigid.

For strength classification it is widely accepted that a joint may be classified as nominally pinned if its design moment resistance, $M_{j,Rd}$, is not greater than 0,25 times the design moment resistance required for a full-strength joint. In case the moment resistance is greater than or equal to the member design moment resistance, it is full a strength connection.

It can be concluded that the classification of connections is based on the initial stiffness and moment capacity. The initial stiffness is determined by either rigorous calculation according to BS EN 1993-1-8 (2005), FE analysis, or experimental testing, all of which are non-standard design practices in the UK because they require time and expertise. The eccentric end plate connections require non-standard design practice as design guidance is only provided for standard simple connections; the UK national annex for 'BS EN 1993-1-8' states that '*Nominally pinned joints are described as ''Simple Connections'' in UK practice.* Connections designed in accordance with the principles given in the publication 'Joints in Steel Construction – Simple Connections' may be classified as nominally pinned joints' (Eurocode 3, 2005). The classification is impossible to be suggested for details that fall outside of the guidance publication requirements and should be determined with the non-standard design methods aforementioned. Consequently, this paper aims to investigate the rotational behaviour of the EEP beam-to-beam connection to determine its classification and compare it to the FP and PDEP connections.

1.3 Eccentric End Plate Connections

Figure 1 and 2 present the complexity in geometry of beam-to-beam connections and confirms that standard connections would not be suitable for these situations, thus an EEP connection is commonly used.

Figure 1 **- Beam to Smaller Beam with Eccentric End Plate; Construction site photos by D.A. Hawxwell (co-author)**

Figure 2 **- Beam to Skewed, Higher Beam with Eccentric End Plate; Construction site photo by D.A. Hawxwell (co-author)**

SCI P358 (2014) provides a section for alternative design solutions titled 'special connections', otherwise known as 'non-standard connections', for situations with complex geometries. The EEP connection chosen in this study presents a large difference in level.

The EEP connection is considered as a non-standard connection and SCI P358 (2014) does not provide any design check requirements. By reviewing the principles given for the FP and

PDEP connections the following load path can be presumed; the shear force is assumed to be transferred through the secondary beam web, through the weld in to the secondary end plate, through the bolt group in to the primary end plate, through the primary end plate weld in to the stiffeners, and through the stiffener weld in to the primary beam.

The position of the end plate is at an eccentric distance from the support member. Fin plate bolts are also eccentric and have to be designed for the eccentric shear, therefore the same principle is often applied in practice to the eccentric end plate with full-depth end plates designed for the shear multiplied by the distance from the line of shear. The principle is in agreement with the previous version of SCI P358 (2014), SCI P212 (2002), and designed in accordance with BS5950-1 (2005) which states that: *'to avoid the effects of torsion on the supporting beam, design bolt group, tees and end plates to resist moment of (F_v e)'*. This suggests that the connection may not be nominally-pinned, hence the reason for the current investigation.

1.4 Fin Plate Connections

A FP connection, as shown in SCI P358 (2014), consists of a plate welded to the web of the primary beam and bolted to the web of the secondary beam. It also provides a standardised geometry with fittings of steel grade S275. Substituting steel grade S275 with S355 is often used by steel fabricators, however this is beyond the standard detail, and thus further investigation is needed.

1.5 Partial-Depth End Plate Connections

A PDEP connection, as shown SCI P358 (2014), consists of a plate welded to the web of the secondary beam and bolted to the web of the primary beam. It provides a standardised geometry with fittings of steel grade S275 (similar to the fin plate). Substituting steel grade S275 with S355 is often preferred by the steel fabricators, however this is beyond the standard detail, and thus further investigation is needed.

2 Experimental Studies

A testing rig was set up for experiments on three connection types with each test repeated three times to confirm the performance, therefore, a total of nine fabricated specimens were studied. The connection types were:

- Test 1 – Eccentric End Plate Connection
- Test 2 – Fin Plate Connection
- Test 3 – Partial-Depth End Plate Connection

2.1 Specimen Details

A 406x140x39UB steel section was chosen as it is widely used in steel structures (e.g. composite beam span-to-depth ratio is often span/25, therefore a 10m span would give around 400mm depth), hence large volumes of such sections are annually fabricated. General geometry of specimen details is based on SCI P358 (2014) and is shown in Figures 3, 4, and 5. EEP connection specific design details are not available, thus the design is based on technical experience and the illustration shown in Table 1 of SCI P358 (2014) with parameters as shown in Table 1. All fittings are of steel grade S355; typically used by some steel fabricators for commercial applications; the steel quality certificate provides the UB properties as f_y=391N/mm^2 and f_u=528N/mm^2.

Table 1 – Eccentric End Plate Connection Specimen Details

Element	Size	Reason
Primary Beam	406x140x39UB, grade S355	This is a common UB section and steel grade for use in buildings, the section size is approximately midrange of the steel sections table.
Secondary Beam	406x140x39UB, grade S355	
Beam Level Difference	+100mm	This provides suitable spacing to allow a row of bolts between the beam flanges, and 100mm increments can be used for the parametric study.
Upper and Lower Stiffener	10mm thick	10mm thick is common for ductile connections.
End Plates	10mm thick	
Bolts Type	8No. M20, grade 8.8	These are standard bolts for simple connections and are also

		recommended for moment connections.
Bolt Gauge	90mm gauge	This is recommended for simple connections and moment connections.
Bolt Vertical Spacing	100mm spacing, first row 50mm from top of steel	This is to suit the beam geometry allowing the parametric study to alter the beam level difference in 100mm increments without the bolts clashing with beam flanges.
Loading Stiffeners	20mm thick	This will allow stress distribution in to the beam web.
Connection to Testing Columns	20mm thick end plates connected by 45mm steel rods	This will provide a stiff connection to the column therefore the primary beam end connections do not affect the study.

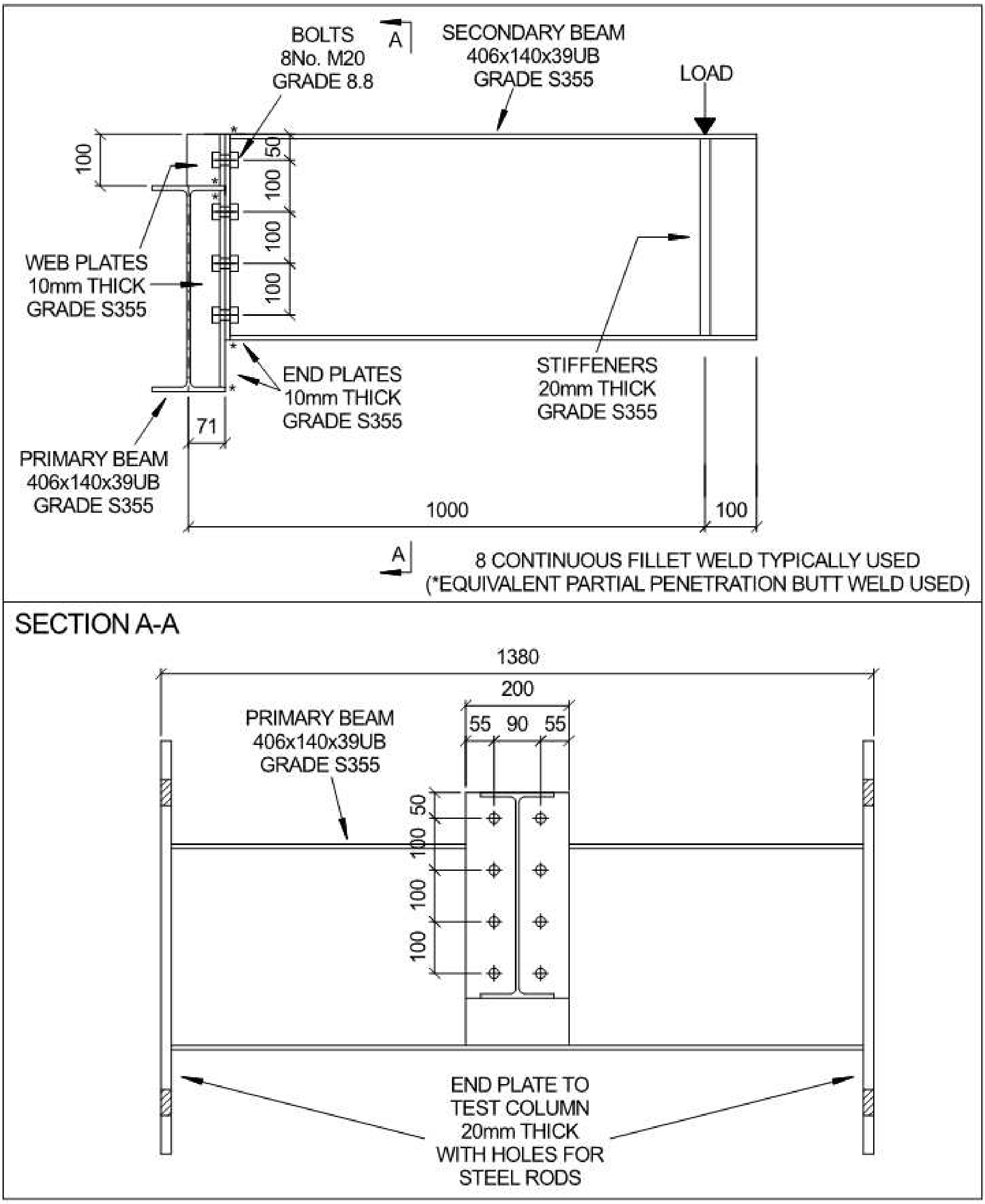


Figure 3 - Eccentric End Plate Connection Test Specimen

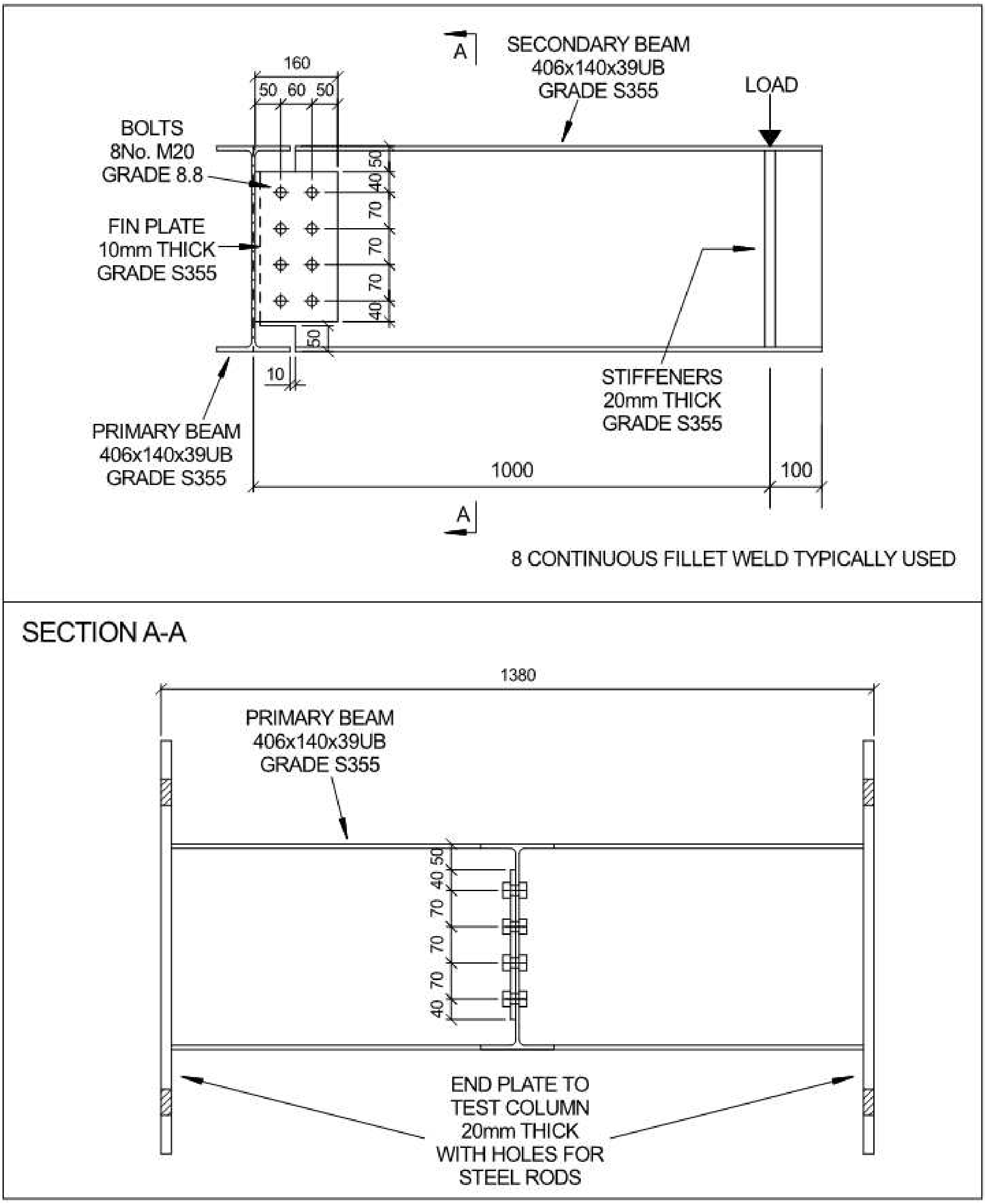


Figure 4 - Fin Plate Connection Test Specimen

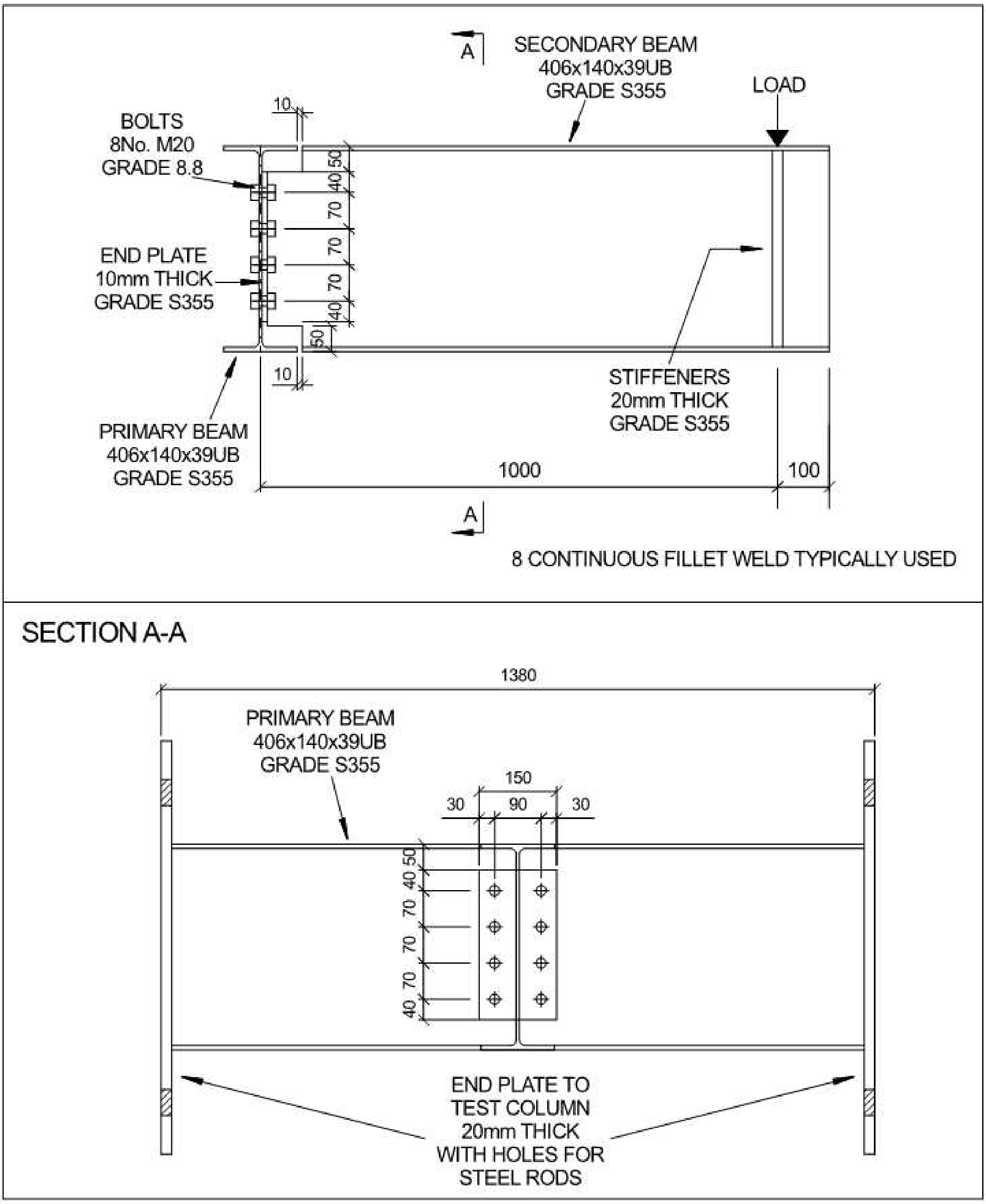


Figure 5 – Partial-Depth End Plate Test Specimen

2.2 Test Procedure

A horizontal T-stub arrangement was set up with the primary beam connected to the testing rig columns and the secondary beam stub connected horizontally to the centre of the primary beam. A monotonic load was applied incrementally (with a loading rate of 5mm/min) in the vertical direction at the free end of the secondary stub beam at 1m from the centreline of the primary beam such that the applied load in kilonewtons is equivalent to the applied moment of kilonewtons metre (i.e. 1kN at 1m distance = 1kNm). The testing apparatus was most practical to load up from the floor. Figures 6, 7, and 8 show the test set up for the eccentric end plate, fin plate, and partial-depth end plate, respectively. Each test was repeated three times to determine average results for better accuracy and eliminate the effect of any geometric and material imperfections.

The deformation was measured with LVDT gauges; two LVDT gauges were placed on the back of the primary beam web at 300mm centres about the beam centreline to measure the rotation of the primary beam; the third LVDT was placed at the end of the secondary beam to measure the vertical deflection, this gauge was placed at 850mm from the centreline of the primary beam to avoid clashing with the loading stiffeners above the hydraulic jack.

Single direction strain gauges were applied to the secondary beam web at 300mm centres about the beam centre line, as described in **section 2.3.3**. For the FP and PDEP connections, the strain gauges were positioned to the corner of the notch; EEP connection does not incorporate notches. The gauges were in the direction parallel to the secondary beam span and were used to measure the stress distribution in the beam near the connection.

Single direction strain gauges were also applied to the fittings of each connection to assess how the moment is distributed through the connection; the locations of the gauges are shown in **section 2.3.4**. For the EEP connection, the strain gauges were positioned to the top stiffener centre between the top bolts and primary beam top flange and on the primary end plate 50mm above bottom of steel. For the FP and PDEP connections, the gauges were applied to the top, middle, and bottom of the fitting plates.

Figure 6 - Eccentric End Plate Test Arrangement

Figure 7 - Fin Plate Test Arrangement

Figure 8 – Partial-Depth End Plate Test Arrangement

2.3 Experimental Results

The following section describes the behaviour that was observed during the tests of each arrangement.

2.3.1 Moment-Rotation Relationship

Figure 10, 11, and 12 show the maximum rotation captured of the three tests; eccentric end plate (EEP), fin plate (FP), and partial-depth end plate (PDEP) connection arrangements, respectively. It was observed that the EEP connection required a higher load to rotate in comparison to the other two connections.

The EEP connection initially caused rotation in the primary beam with minimal deformation in the connection. At approximately 25kN, the primary beam plasticity commenced causing it to rotate at a faster rate. At approximately 43kN the flange of the primary beam started to buckle as discussed in **section 2.3.2**.

The FP connection allowed slipping in the bolts at approximately 7kN, as the graph shows a levelled period. The PDEP connection did not allow bolt slipping. Both the FP and PDEP connection tests required less amount of force than the EEP connection to rotate. Each test was loaded and it was observed that most of the deformation occurred in the primary beam web with minimal deformation in the fittings or the primary beam flanges. At approximately 0.04 radians, the flanges of the primary and secondary beam met (in contact) each other and so started causing displacement of the primary beam flanges and rotation in the primary beam.

As discussed in **section 1.2**, connections can be classified as nominally-pinned, semi-rigid, or rigid, based on the initial stiffness and the strength. The three experiments have been analysed to determine the classification of the connections using trigonometry of the LVDT values to calculate the rotation of the primary beam and the secondary beam.

For stiffness, the boundaries for nominally-pinned and rigid connections have been calculated from equations of '$S_{j.ini} = 0.5\ EI_b/L_b$' and '$S_{j.ini} = k_b\ EI_b / L_b$', respectively, assuming k_b as 8 and length of beam (L_b) as 10m between primary beam supports. This is a realistic span for a beam of section size UB406x140x39 in composite construction based on span-to-depth ratio.

In addition, the building is assumed to be braced for the rigid boundary. For strength, the boundary is based on the 25% of the secondary beam moment resistance (SCI P398, 2013), therefore, 0.25 x 257kNm is equal to 64.25kNm.

The results, as shown in Figure 9, demonstrate that the FP and PDEP connections with steel grade of S355 fittings are classified as nominally-pinned, while the FP connection is performing more ductile than the PDEP connection. The EEP connection is classified as semi-rigid - also bordering on rigid.

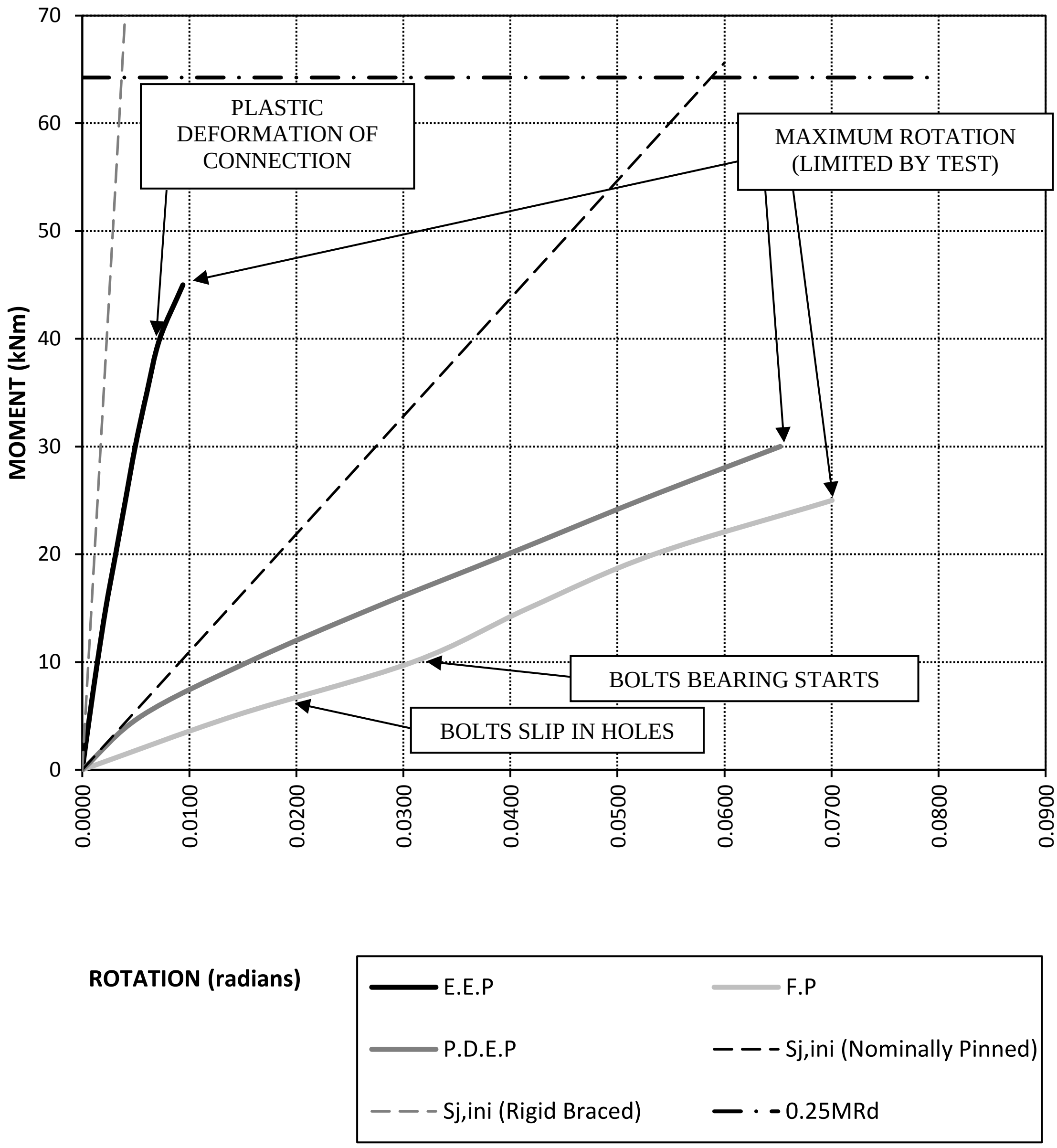


Figure 9 **- Moment / Rotation Curves – Connection Classification**

Figure 10 - Eccentric End Plate – End Deflection

Figure 11 - Fin Plate – End Deflection

Figure 12 – Partial-Depth End Plate – End Deflection

2.3.2 Failure Mechanisms

The load was applied to each test until limits of the hydraulic jack were reached and then terminated with observations of any failure mechanisms noted. It was found that due to the specific characteristics of the three different types of connections, each set of tests produces different failure mechanisms which are herein described separately.

Eccentric End Plate Failure Mechanisms

The failure mechanism of the EEP connection test is demonstrated in Figure 13. This connection resisted the highest applied load out of the three different connection tests before a failure mechanism occurred at approximately 43kN. Initially, it was observed that the loading causing rotation of the primary beam was excessive in comparison to the minimal deformation of the end plates or stiffeners of the connection. Therefore, it is suggested that the support is too flexible in comparison to the connection and a larger gap between the end plates would have been expected had the connection provided more ductility. The behaviour of the connection appears to be the same as the design procedure of an end plate moment connection in SCI P398 (2013); i.e. the moment is transferred by tension in the bolts and compression in the bottom flange of the secondary beam, which then transfers in to the stiffener plates of the primary beam and then to the bottom flange of the primary beam, hence the reason for the excessive rotation. The primary beam started to deform more excessively at approximately 25kN, thus passing its elastic yield strength and becoming plastic. The primary beam flanges displaced relative to the rotation of the primary beam at the centre while they were rigidly fixed to the columns of the testing rig. Consequently, the lateral bending caused the bottom flange to buckle at approximately 43kN. The buckling occurred on the connection side of the primary beam and the end plate welded to the flanges provided stiffness to the centre of the beam. Therefore, the buckling of the flange occurred locally to each side of the end plate.

Figure 13 - Eccentric End Plate Failure Mechanisms

Fin Plate Failure Mechanisms

The failure mechanism of the FP connection tests is depicted in Figure 14. FP connection resisted the lowest applied load out of the three different connection types before a failure mechanism occurred at approximately 25kN. During testing the web of the primary beam rotated rather than the whole section as observed in the EEP connection test, at approximately 15kN the bottom flanges of the beams met each other (in contact) causing further rotation in the primary beam. Two failure mechanisms occurred at approximately the same time; buckling of the primary beam top flange as well as tearing of the primary beam web at the top of the fin plate. Such failure mechanism suggests that the fin plate distributes moment stress to the primary beam, intensified by the contact of the bottom flanges to cause a moment force between the flange contact in compression and the fin plate top in tension. The tension force in the top of the fin plate was sufficient to tear the primary beam web and buckle the primary beam top flange which occurred on the side opposite to the connection, instead of the same side as observed in the EEP connection test.

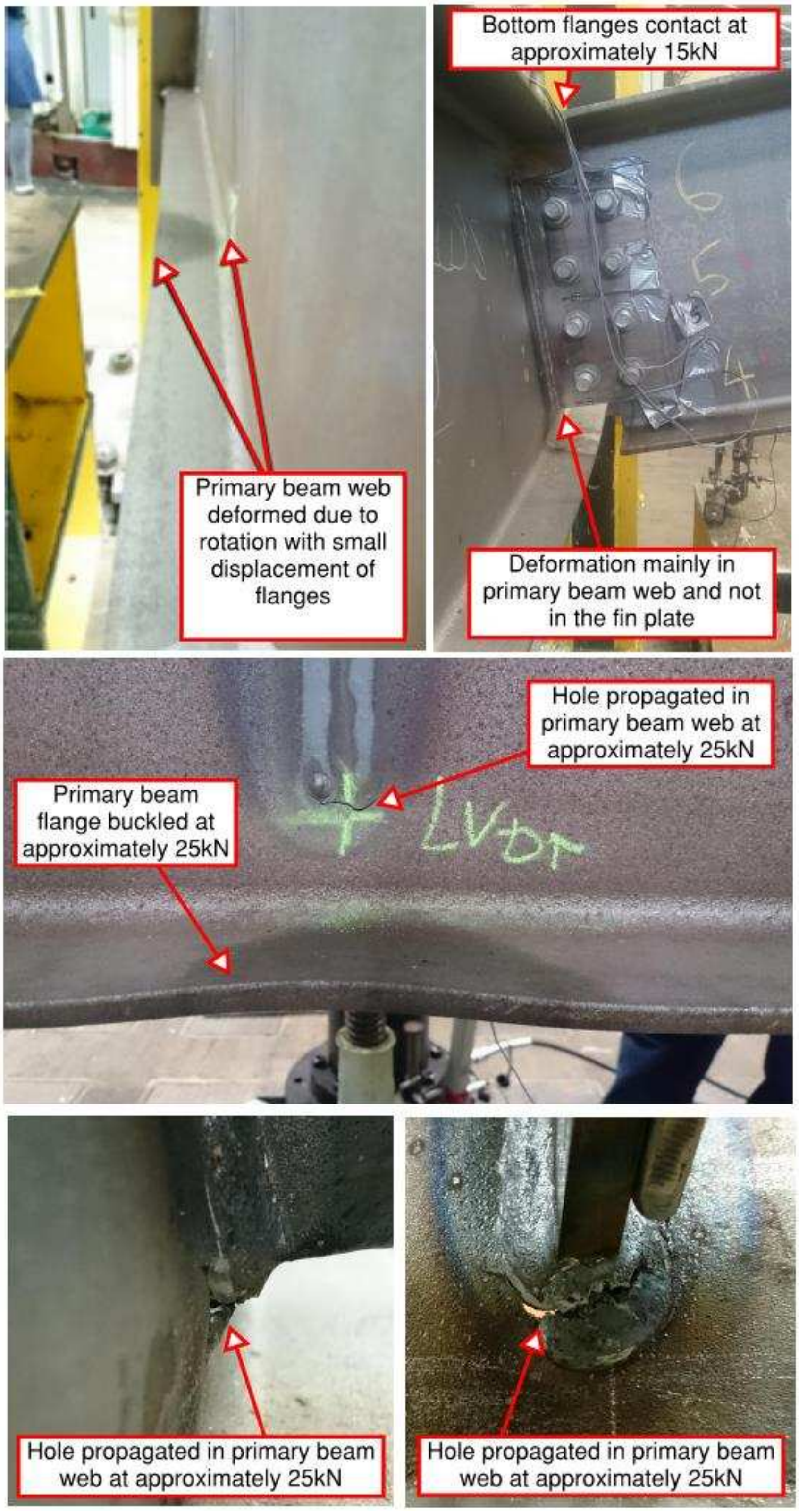


Figure 14 - Fin Plate Failure Mechanisms

Partial-Depth End Plate Failure Mechanisms

The failure mechanism of the PDEP connection tests is observed in Figure 15. This connection resisted much lower applied load than the EEP connection but slightly higher than the FP connection before a failure mechanism occurred at approximately 29kN. The behaviour of the PDEP connection was similar to the behaviour of the FP connection. The primary web deformed initially, although local to the bolts, as they are bolted to the web as opposed to a fin plate welded to it. At approximately 17kN, the bottom flanges met each other (in contact) causing a compression force on the bottom flange, and therefore, additional moment resistance transferred in to the primary beam. Only one failure mechanism occurred for this test as the tension force in the top bolts was sufficient to buckle the primary beam top flange which occurred on the side opposite to the connection, similar to that observed by the FP connection test, instead of the same side as observed in the EEP connection test.

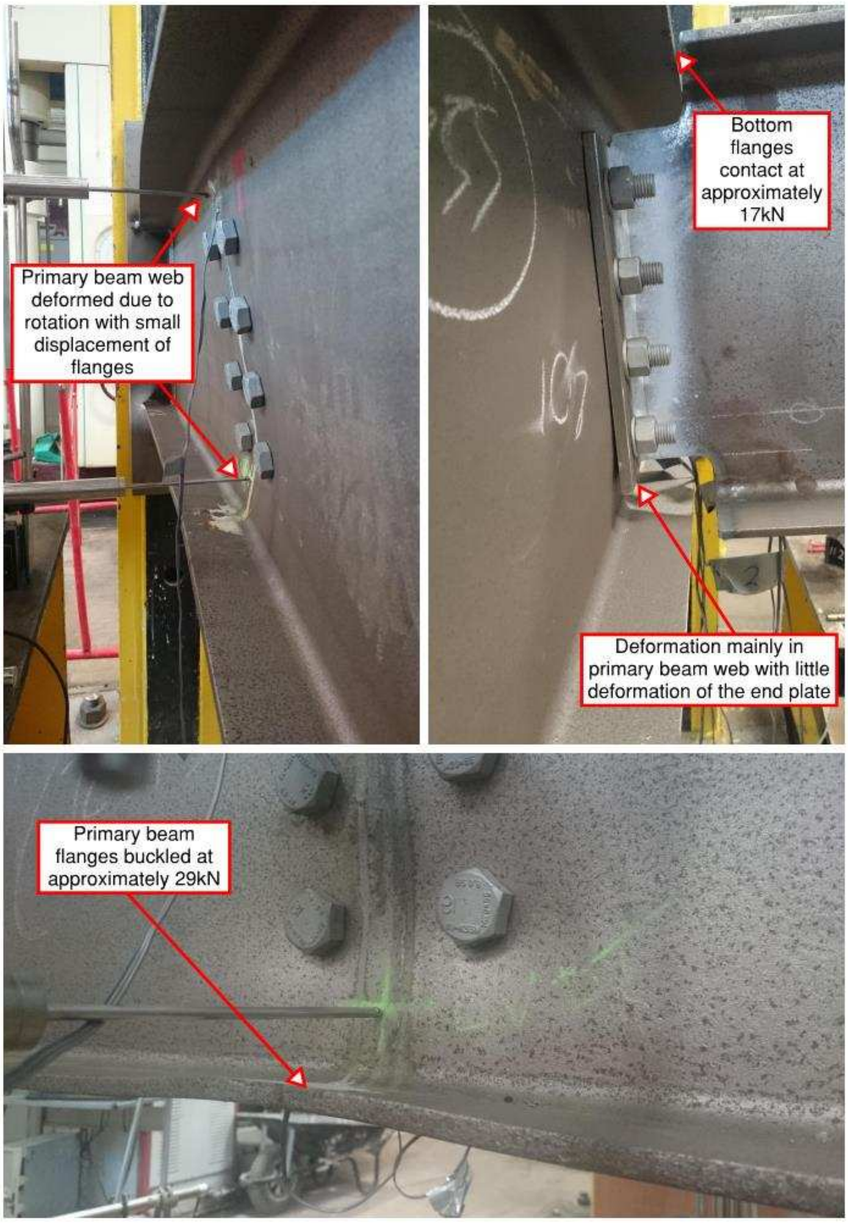


Figure 15 – Partial-Depth End Plate Failure Mechanisms

2.3.3 Strain on Secondary Beam Web

Single direction strain gauges were applied to the web of each secondary beam to observe the stress distribution. Figure 16 shows the location of the gauges (50mm between each flange and web mid-depth) and the recorded strains at the top, middle, and bottom of the secondary beam web.

It is observed that the EEP connection was subjected to a linear distribution with high tension at the top, low tension in the middle, and high compression in the bottom; this result is expected because a moment was applied to the connection with a full beam section. The FP and PDEP connections' distribution changed when the bottom flanges came in to contact at excessive rotation. Prior to contact the beams were subjected to tension in the top and compression in the middle and bottom. After contact, the compression in the bottom and middle of the beam web reduced and then went in to tension, the top stayed in tension but the strain increased at a slower rate than before the flanges met each other (in contact), because the tension strain was distributed over the whole web. The tensile strain in the bottom of the web on the FP connection increased more than the gauge on the middle, as the gauge was located near the notch where concentration can occur; this was not observed on the PDEP connection.

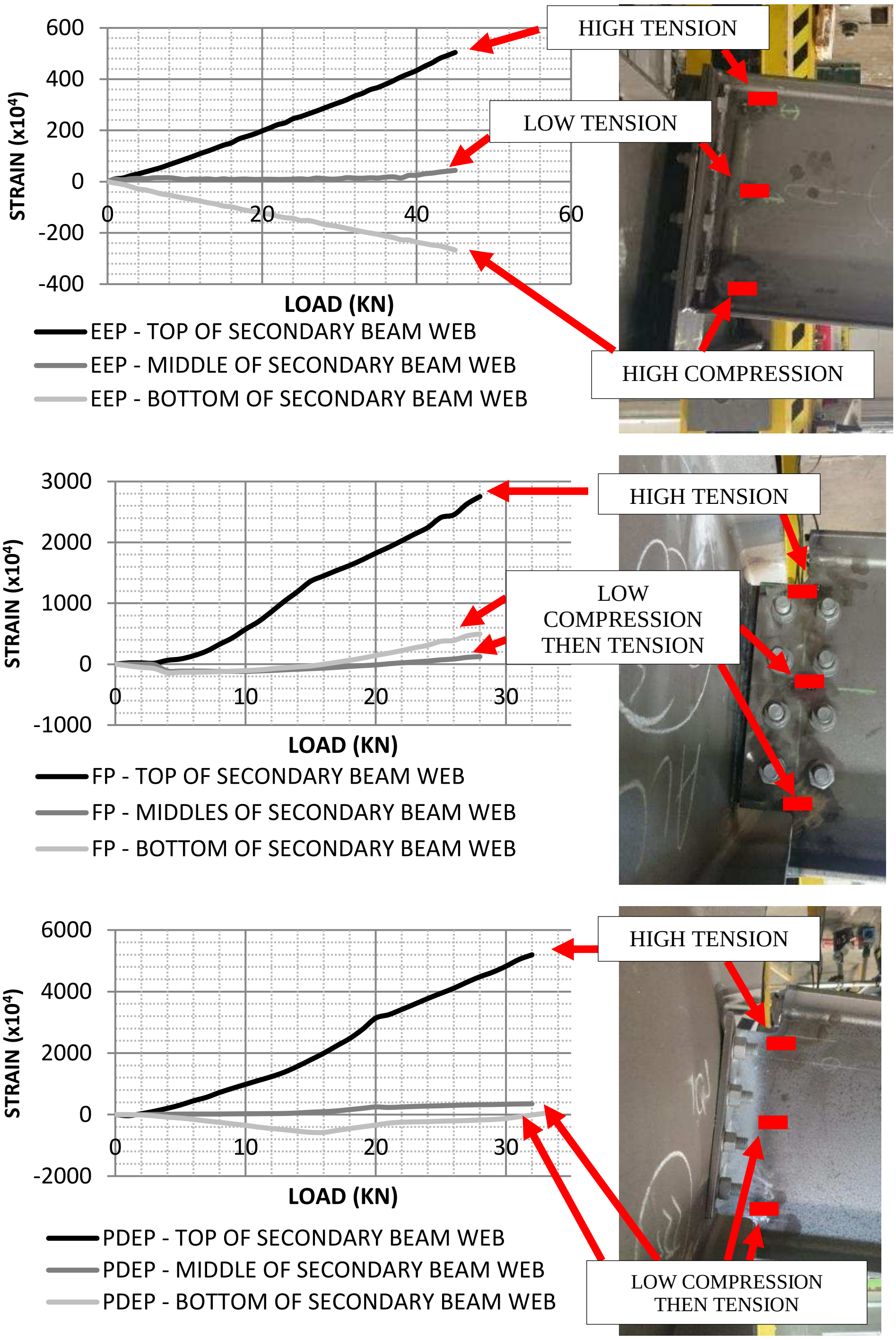
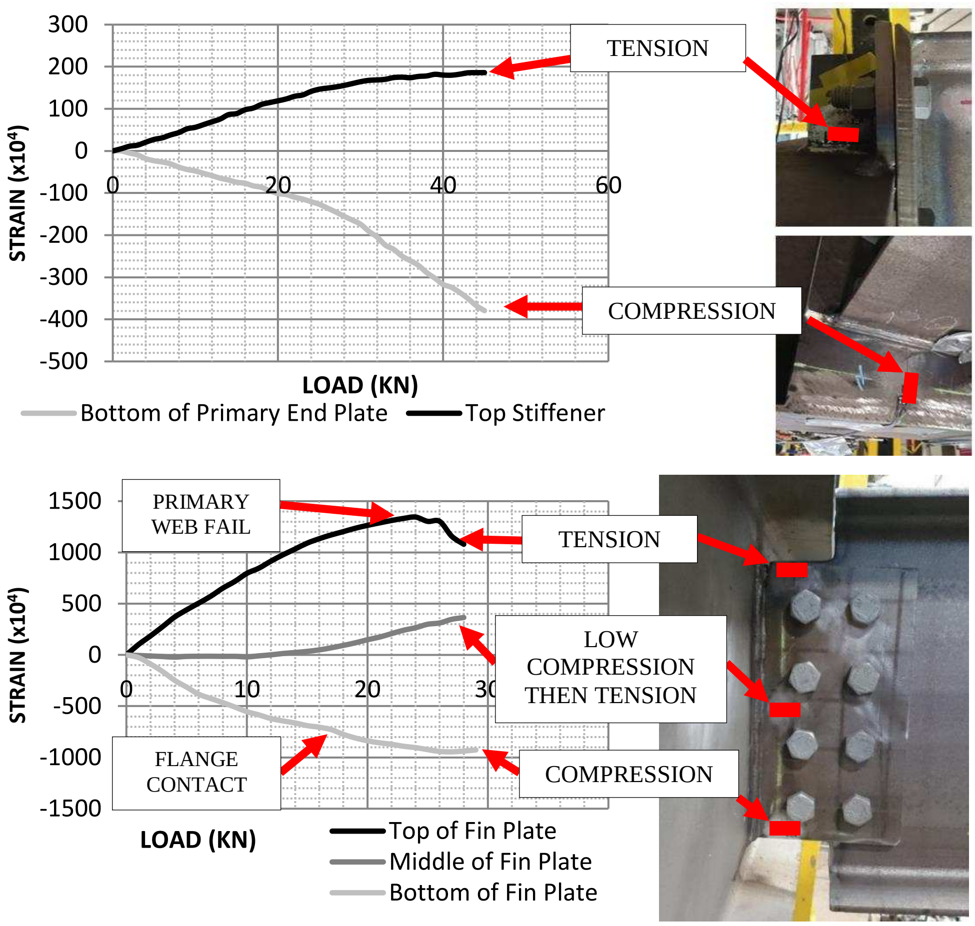


Figure 16 **- Strain on Secondary Beam Web: EEP (top) / FP (middle)/ PDEP (bottom)**

2.3.4 Strain on Connection Fittings

Single direction strain gauges were applied to the fittings of the connection. Figure 17 shows the location of the gauges and the recorded strains. EEP connection results demonstrate that moment is distributed through the end plates into the beam. FP connection results demonstrate that the fin plate carries a moment, thus, not all stresses released in the bolts. PDEP connection results demonstrate that the end plates are yielding even though this was not clearly visible.



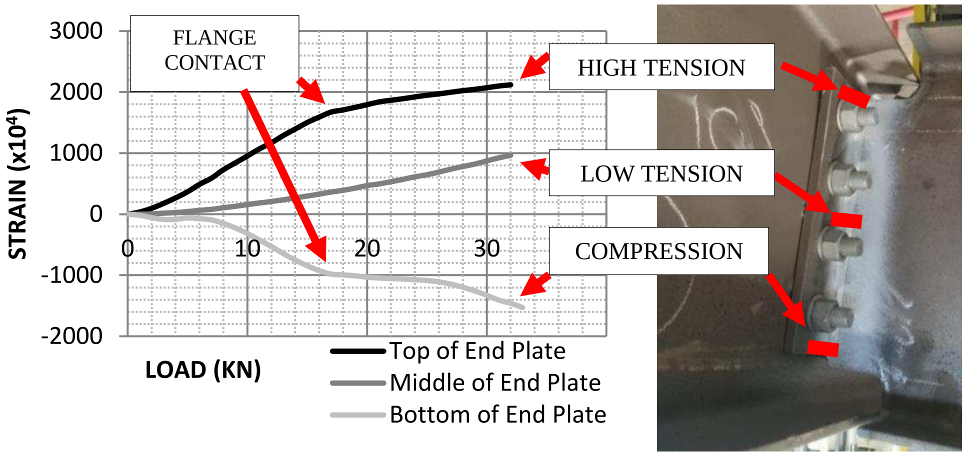


Figure 17 – Strain on Connection Fittings

EEP (top) / FP (middle)/ PDEP (bottom)

3 Concluding Remarks

Nine beam-to-beam connections of three different types were experimentally investigated, to compare and classify them against current design specifications. All connections promoted a failure mechanism in the primary beam as described in **section 2.3**, however these failure mechanisms occurred when the beams had rotated excessively, more than a real situation of a simply supported beam. It is important to note that the contact of the flanges of fin plate and partial-depth end plate was also due to the excessive rotation.

All connections demonstrated some moment resistance; however, the eccentric end plate (EEP) connection was the stiffest connection type of the three. It also caused the most rotation of the primary beam due to the stiff joint between the two beams. Out of the three tested specimens, it is summarised that the fin plate (FP) and partial-depth end plate (PDEP) connections with steel grade of S355 fittings can be considered as nominally-pinned connections, whereas the eccentric end plate (EEP) connection with the parameters used should be considered as a semi-rigid connection.

Section 2.3.1 shows that the EEP beam-to-beam connection is classified as semi-rigid for a 406x140x39UB with boundaries calculated based on a 10m span between primary beam supports, thus, this should be taken into account in the frame analysis. The primary beam is mainly deforming while the whole beam rotates, and thus, dispersing stresses in to the flanges. When subject to excessive rotation the primary beam is involved in the critical failure mechanism with flange buckling.

A FP beam-to-beam connection with standard geometry and steel grade S355 fittings is classified as nominally-pinned when used for a 406x140x39UB with boundaries calculated based on a 10m span between primary beam supports. The primary beam is mainly deforming as the primary beam web rotates, however the connection does provide sufficient ductility for nominally-pinned requirements. When subjected to excessive rotation, the primary beam is involved in the critical failure mechanism with flange buckling and web tearing.

A PDEP beam-to-beam connection with standard geometry and steel grade S355 fittings is classified as nominally-pinned when used for a 406x140x39UB with boundaries calculated based on a 10m span between primary beam supports. The primary beam is mainly deforming as the primary beam web rotates. However, the connection does provide sufficient ductility for nominally-pinned requirements. When subjected to excessive rotations, the primary beam is involved in the critical failure mechanism with flange buckling.

The EEP beam-to-beam connection in this experiment is categorised as semi-rigid with a higher stiffness and strength than the FP and PDEP connections tested which are categorised as nominally-pinned. The EEP connection has also the higher impact on the primary beam, causing unwanted torsion.

From this study, it is suggested to only use EEP connections if the fixity has been considered in the frame analysis or by proving the specific connection on a project by other means, such as FE analysis / experimental testing / analytical calculations specific to the project, to be nominally-pinned.

This research can be developed further with the review of various configurations of the connections including plate thickness, primary beam size, secondary beam size, and bolt arrangements.

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