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Experimental Investigation on Steel Bracing Connection Through Hinge Plate

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Abstract: Bracing elements and their connections have played a key role in the steel bracing frame energy dissipation through yielding and buckling. Whereas it is normally expected that gusset plates yield and buckle after that of bracing elements. Moreover, bracing elements buckling go with the plastic hinge formation in gusset plates. However, the geometry requirement to provide plastic hinge formation leads to larger and consequently thicker gusset plate. This article presents a research concerning steel bracing connection detail. In this proposed steel bracing connection, Hinge Plate manages the formation of the plastic hinge in the bracing connections. To verify the proposed idea a monotonic compression test was conducted on a bracing element; that was detailed with Hinge Plate. As a primary observational goal of the test, buckling mode of bracing element was depicted to be well managed by Hinge Plate. In addition, it was observed that the hierarchy of yielding in bracing element and then in Hinge Plate coincided with expected energy dissipation requirement in bracing frame.

Keywords: Bracing connection · Gusset plate · Plastic hinge · In-plane buckling

INTRODUCTION

Bracing elements in concentrically steel braced frame (CSBF) are designed to provide lateral load resistance and energy dissipation through yielding and buckling due to tension and compression respectively. The expected proper energy dissipation pattern is specified in two important characteristics. Firstly, the bracing section yields in tension before its connection in gusset plate. Secondly, the detailing in gusset plate allows the bracing element to buckle in compression before any local or global buckling in gusset plate. Indeed, the buckling starts with constitution of plastic hinge in mid-length of bracing elements, where the intensive stresses initiate the local buckling. Designed gusset plate has to provide enough capacity to meet the foregoing buckling procedure. In a way, buckling of gusset plate, before that of bracing element, provides unpleasant failure.

In this regard, design codes [1] express three clauses for gusset plate design limitation. First, the minimum required tensile strength of gusset plate has to conform to expected yield strength of, $R_Y F_Y A_g$ where; R_Y= 1.1 to 1.5, F_Y= yield stress and A_g= bracing section area. Second, it has to provide at least 1.1 times of the expected brace compression strength. Finally, the gusset plate has to satisfy the plastic hinge formation with the brace terminating before the line of restraint (Fig. 1a).

The importance of plastic hinges formation for appropriate bracing element behaviour is emphasised. Development of plastic hinge formation on bracing elements is narrowed down by Astaneh-Asl *et al.* [2]. This study is now considered as one of the basic reference in American Institute of Steel Construction (AISC) [3]. To meet this requirement, gusset plates become larger and consequently thicker [4]. Many researchers have considered this outcome and tried to develop alternative theory to reduce gusset plate size together with plastic hinge formation. In Fig. 1b elliptical clearance band pattern is used for plastic hinge formation [5]. Another research has presented the three line pattern for plastic hinge [6]. These researches [5, 6] assumed that gusset plate perform a twofold function of load transferring and plastic hinge formation. Similar assumptions are also used by other researchers [2, 4].

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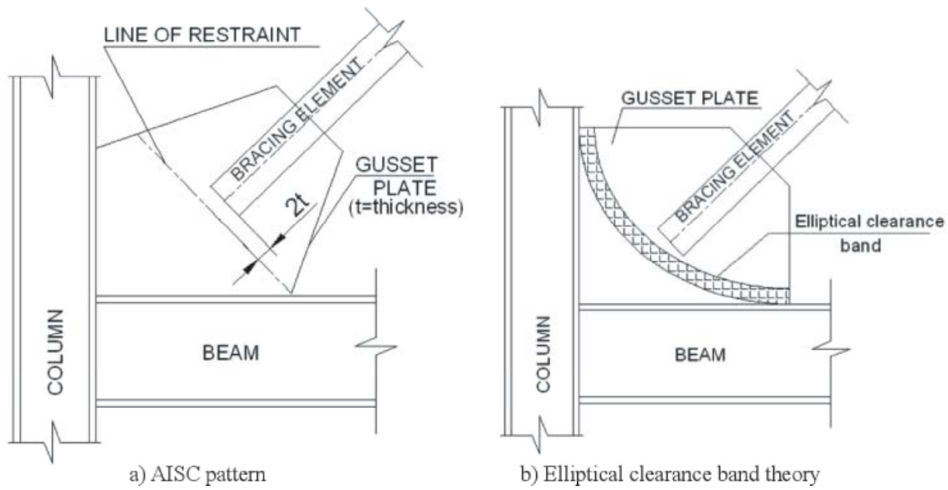


Fig. 1: Plastic hinge patterns

Indeed, it is desirable to utilize one structural element for two demanding functions, if their criterion satisfactions are not in opposite direction. In case where the plastic hinge formation line is not likely to happen, then the gusset plate dimensions become smaller.

The purpose of this paper is to present an alternative proposal of steel bracing connection through hinge plate. Accordingly, an experimental study is designed and conducted to examine the proposed bracing connection details.

Reaserch Significance: The twofold functions (load transfer and plastic hinge formation) of conventional gusset plates have resulted numerous problems in bracing steel framing design and fabrication. Gusset plate size, buckling modes (in-plane and out of plane) and energy dissipation are few of them. Both the larger and thicker gusset plates are exacerbated from the fulfilment of the code dimension limitation on plastic hinge formation in gusset plates. Consequently, these plates afford moment resistant beam-column connections which is far apart of using the conventional truss modelling in steel brace frame analysis [4].

Mostly in conventional bracing elements out of plane buckling mode governs in design. As in-plane buckling length is smaller than out of plane buckling length then proper selection and detailing design of bracing elements section and its connection detail are determinant points to alter buckling mode to in-plane mode. Additionally energy dissipation through in-plane buckling mode is more efficient than the out of plane buckling mode. Hinge Plate is expected to diminish the aforesaid problems as is tested and presented in this paper.

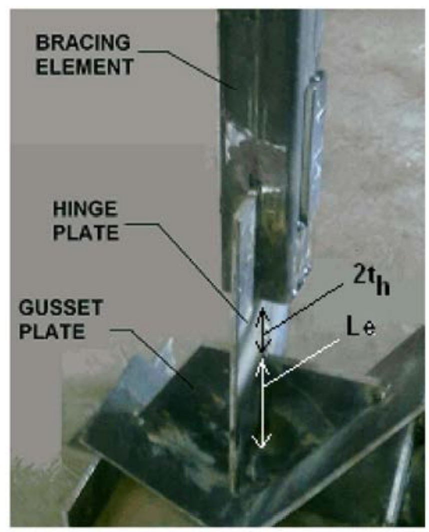


Fig. 2: Hinge Plate (HP)

HING PLATE (HP): In this research, the plastic hinge formation line is transferred to an additional plate, called Hinge Plate (HP) as shown in Fig. 2. In this arrangement, gusset plate geometry is no longer affected by plastic hinge formation.

Compared to conventional bracing connection, which bracing element transfers load to gusset plate, in proposed detail the load path goes from bracing element primarily to HP and then continues through gusset plate. HP design features obey the same rules as gusset plate requirements; but its geometric dimensions are mostly dedicated for plastic hinge formation. The formation of plastic hinge is provided in HP by a minimum clearance space equal to double HP thickness as required by AISC [1].

MATERIALS AND METHODS

In cross-braced steel frame two joints of steel frame is connected through bracing element. Gusset plates are connected to beam column connections via fasteners (welding or bolts). The testing is setup to represent the actual condition of HP connection detailing in conventional steel frames. The testing specimen is a cut of bracing element from joint "A" to brace crossing point (Fig. 3).

The full-scale specimen is composed of bracing element, HP, gusset plates and beam-column connections at both ends of the bracing element. Gusset dimensions and beam-column elements alignment simulate the geometry of the real frame by taking account the relative angle of bracing with beam and column. The primary detailing designs are based on AISC [1]. Bracing element is a hollow box section 50x50x2.7 mm. It is made of cold formed steel with nominal yield strength of 400 N/mm^2 and an ultimate strength of 450 N/mm^2. The bracing element length is 1020 mm due to the limitation of the testing rig. The HP yield strength of 290 N/mm^2 and an ultimate strength of 430 N/mm^2 are employed. Its cross section is 110x6 mm. Distance of (2t_h) from the end of bracing element to start of gusset is satisfied in HP where t_h is the HP thickness (Fig. 2). It is supposed that HP employs in-plane buckling mode in cross steel bracing frames under loading. Specimen slenderness is 52 (kL/r) which is similar to in-plane buckling mode of cross bracing in common buildings. Gusset plate and HP in bottom support of specimen simulate joint "A" in Fig. 3. Top support plastic hinge in mid-length of bracing is also copied by HP. As depicted in Fig. 4 top support is free just for vertical deflection while the bottom support subassemblies are simulated as bracing element in beam-column connection [7]. The full-scale specimen is assembled, as close as practical to the method used in conventional steel workshops. All elements are connected by welding.

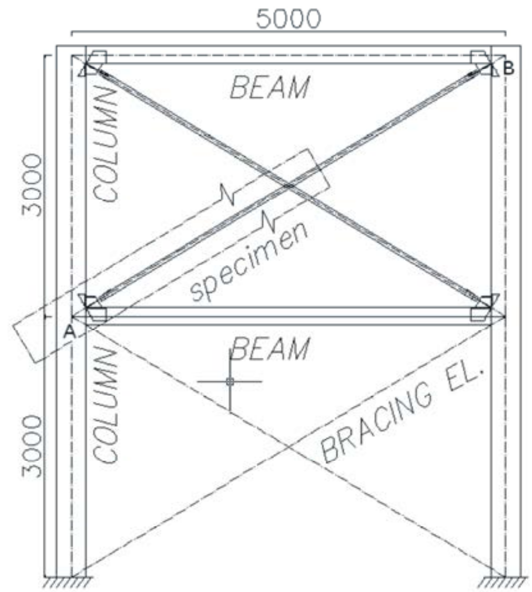
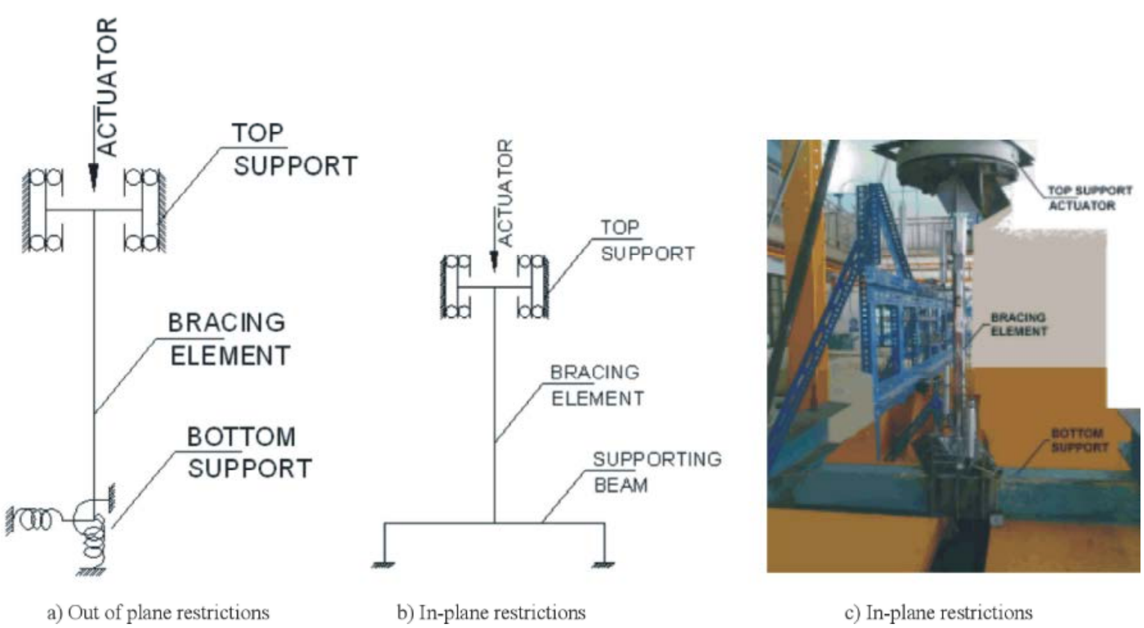


Fig. 3: Specimen cut



a) Out of plane restrictions b) In-plane restrictions c) In-plane restrictions

Fig. 4: Test setup and support restraints

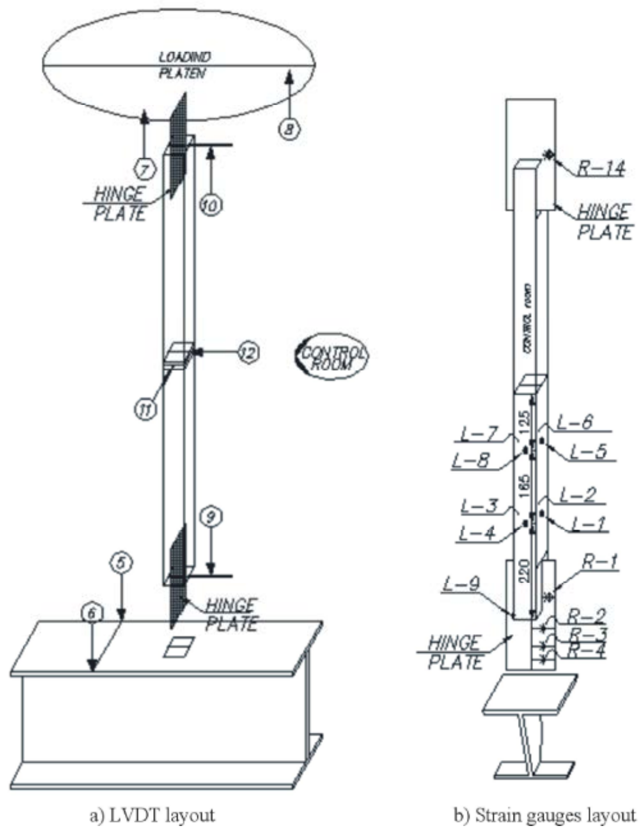


Fig. 5: Device Layout

Loading is applied statically through a hydraulic actuator attached to the top circle platen with maximum load capacity of 1000 kN. Loading is started at zero and increased to failure of the specimen. Imposed loading history is recorded by a load cell which is assembled in the actuator.

In order to record the specimen behaviour, displacements are traced through LVDT (Linearly Variable Displacement Transducers) and strains are recorded by linear and rosette strain gauges. Measurement device layout and data acquisition channel number are indicated in Fig. 5.

All of the data are collected by data logger and interpreted to spreadsheet through special computer software.

RESULTS AND DATA ANALYSIS

Loading history and deformation which are recorded throughout the test program presented the general and distinctive HP behaviour in conjunction with bracing element and supporting condition. The deflection of bracing element in the plane that involve the beam, column and bracing element is gathered by LVDT No. 12. This is shown in Fig. 6 as in-plane deflection. LVDT No. 11 is used to record deflection perpendicular to in-plane deflection and that is also shown in Fig. 6 as out of plane deflection. Buckling behaviour of bracing element is captured by in-plane and out of plane deflection.

The axial loads are applied increasingly over the specimen, simultaneously the out of plane deflection at mid-height of bracing element raises progressively and finally peaked at 7 mm, as is depicted in Fig. 6. However, the in-plane deformation in the specimen almost entirely shows no deflection during the loading process until buckling suddenly take place. Generally, the gradual out of plane deflections is the result of bending behaviour in specimen. In this case, bending deflections arise from initial imperfection and lack of rotation stiffness of bottom support in the specimen (Fig. 4a).

Gradual load increasing is simultaneous with development of larger difference in stress at opposite side face of box section which is recorded by LVDT assigned as L-7 and L-5 (Fig. 7a). Initial imperfection is the main reason for stress difference in mid-height of specimen.

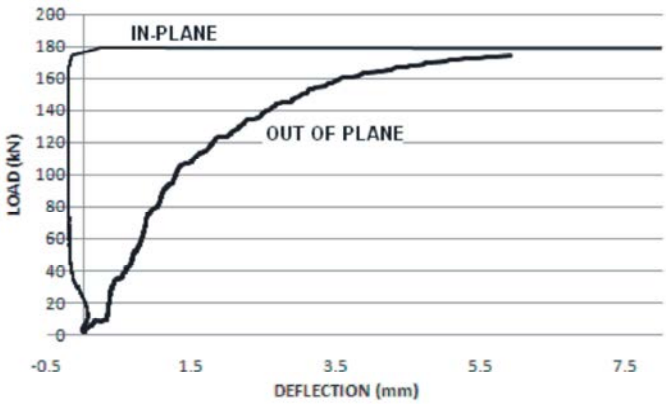
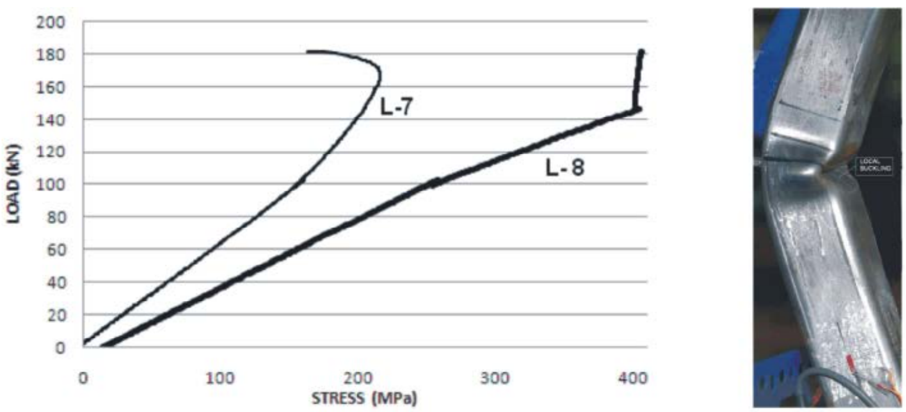


Fig. 6: Load-lateral deflection in mid height of specimen



a) Stress at mid-height of specimen strain gauges L-7 and L-8 b) Mid-height local buckling

Fig. 7: Local buckling at mid-height of specimen

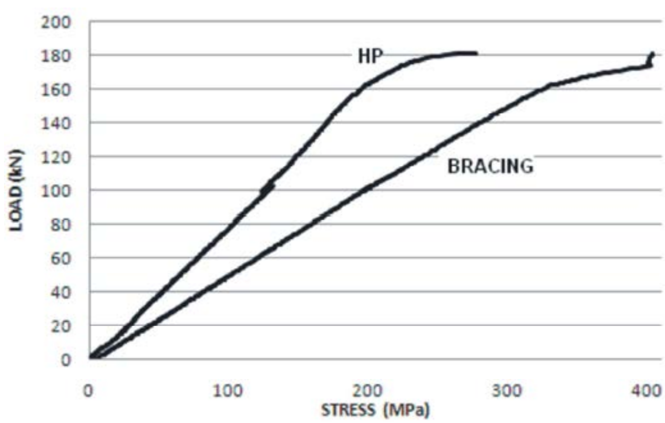


Fig. 8: Load-Stress

When loading meet 130kN the box section yields in one side at mid-height. Development of yielded face resulted in local buckling and formation of first plastic hinge at mid-height of bracing element at the load of 165 kN.

Next to formation of mid-height plastic hinge, at the load of 176 kN the HPs in both ends yield and cause the formation of plastic hinge (Fig. 8). Formation of three hinges is simultaneous with the sudden in-plane buckling deflection at the load of 176 kN.

For the purpose of increasing the reliability of measurements buckling load of specimen is compared in three different methods and revealed in Table 1. First row shows the recorded buckling load by actuator load cell.

Table 1: Buckling Load

Method	Buckling load (kN)	Deviation (%)
Actuator load cell	158	0
Strain gauge base	176	11
AISC (slenderness ratio = 52)	161	2

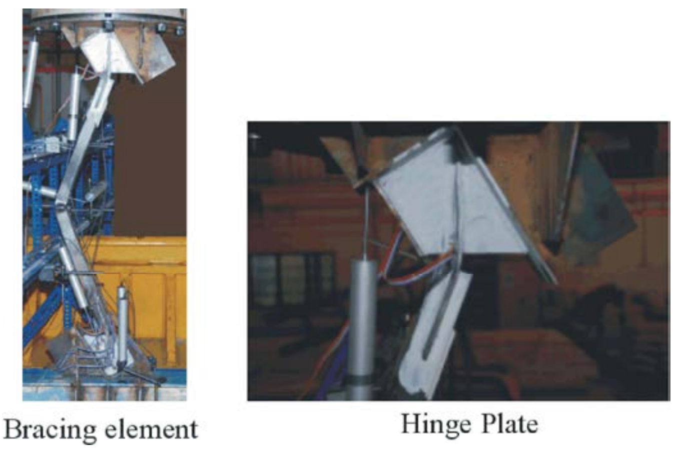


Fig. 9: Specimen deformed shape

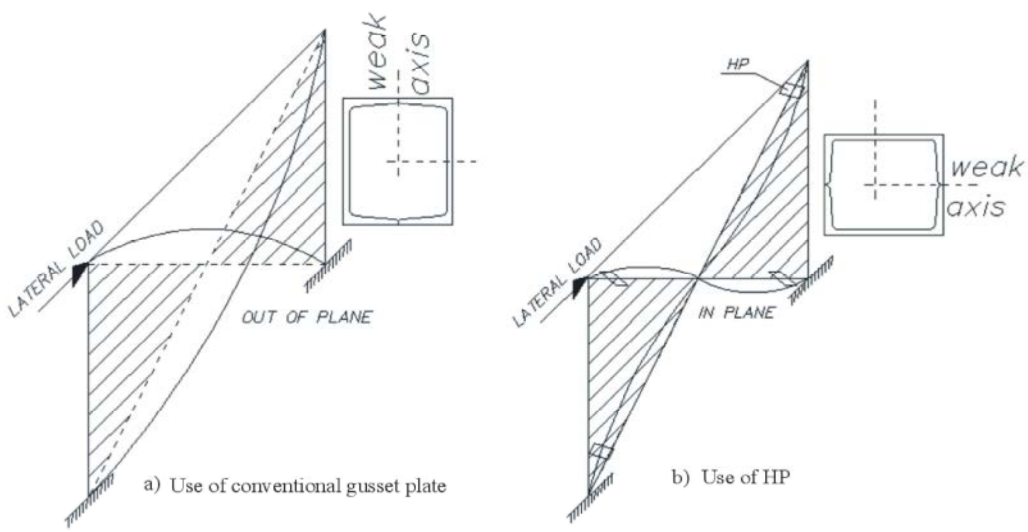


Fig. 10: Buckling mode in bracing frame with different connection detail

Second row, gathered data from eight linear strain gauges (L-1 to L-8) are used to calculated the stress and then converting them to equivalent axial load by multiplying to their relative area. Third row is the calculated buckling load in accordance to AISC. As shown in last column of the table, there is good agreement between the buckling load from test and code.

In general the performed test clearly demonstrated the behaviour of HP in transferring the plastic hinge location from gusset plate to HP at the buckling load. Plastic hinge locations are thoroughly predictable as a result of using the HP (Fig. 9).

In contrast with gusset plate connection, which deals with out of plane buckling in conjunction with the bracing element, HP deals with in-plane buckling. Additionally the weakness in most of the built up steel profiles in buckling through their weak axis is compensated. For instance, in a cross steel bracing frame with double channel section, the employment of HP may result in to in-plane buckling. In which buckling length reduces to half while buckling capacity increases (Fig. 10).

CONCLUSIONS

This experimental study compares bracing connection detailing of conventional and HP through a monotonic compression test. Focus in specimen setup went on specified steel plate named Hinge Plate. HP detailed thoroughly in the formation of plastic hinge. Test results validated HP behaviour in conjunction with bracing element response.

In spite of extra fabrication work such as cutting and welding of HP, the employment of this detail results in reducing the gusset plate thickness and dimensions. Gusset plate thickness reduction results from two factors. First of all it comes out by omitting the plastic hinge geometric limitation on gusset plate. Next the HP extension length (Le) over the gusset plate provides a stiffener for it (Fig. 2); the brief outcome as conclusions are summarized as follows:

- Formation of plastic hinge took place in HP after buckling of bracing element.
- HP is a plate that provides a specified and acceptable area for formation of plastic hinge; thus HP behaviour is more clear and manageable for designer. In addition transferring the plastic hinge to HP is resulted in reducing the gusset plate dimension and thickness.
- HP facilitates the alignment of bracing element to achieve higher capacity, especially in built-up sections.
- The gusset plate dimension and thickness optimized by omitting the plastic hinge formation on its design process.
- The ease of design and fabrication on formation of plastic hinge is more reliable with use of HP.

The paper reported herein was undergoing to explore the general trait of HP. Ongoing test is programmed, in order to corroborate the repeatability of the experimental data recording and improving experimental condition. Since HP is a new suggestion in steel connection detailing, the unknown and or confirmation related subject cover a vast area such as energy dissipation quantitative, stress flow considerations and suggestion for proper dimensions, bracing element buckling length, bracing element slenderness [8], simultaneous functions of gusset plate and HP, effect of axial force eccentricity on proposed detail, cyclic displacement affects, post-buckling behaviour and material property such as yielding patterns, strain hardening and Bushinger effects.

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