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Numerical modelling of dissipative pin devices for brace-column connections

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ABSTRACT

In this paper, the behaviour of dissipative brace-column connection devices is emphasized. The computation is carried out for a single- and double-pin connection device, where the pins are displaced in two configurations: in-parallel and in-line. The study is conducted by using the theoretical and the OpenSees beam model under monotonic and cyclic quasi-static displacement loading. The proposed OpenSees model of the single-pin connection was calibrated against experimental test results found in the literature and the validation was completed when both the experimental and simulated models provided a good match in terms of hysteresis loops and cumulative dissipated energy. Using the same approach, the double-pin connection, in both configurations, was studied through numerical modelling only. The purpose of installing dissipative single- or double-pin connections at the brace-column joints is to preserve brace members to behave in the elastic range, while maintaining their buckling resistance.

1. Introduction of the CBF system equipped with fuses

Earthquake resistant concentrically braced frames (CBF) are able to provide adequate strength and stiffness when subjected to lateral loading. Brace members performing in tension and compression are designed to dissipate energy through tension yielding and inelastic buckling, while the remaining framing components behave elastically. In agreement with the CSA/S16 standard [1], brace factored resistance should be equal to or greater than the effect of factored loads, the slenderness ratio must be less than 200 and the width-to-thickness ratio of the brace element should comply with Class 1 sections. To allow the deformation of the braces in the plastic range, the factored resistance of brace connections shall equal to or exceed both: the probable tensile resistance and 1.2 times the probable compressive resistance of bracing members. In general, the computed design forces for the brace connections may significantly exceed those corresponding to the designed factored shear force obtained in accordance with the NBCC 2010 provisions [2]. Although the above requirements are considered for the design of braces, the amount of energy dissipated in tension is much larger than that in compression, which diminutes in the post-buckling range with the number of cycles [3]. Moreover, in the conventional design approach, the occurrence of inelastic deformations results in the softening of the CBF system [4].

To reduce the probable tensile strength of brace members and, in consequence, minimizing the design force transferred from tensile brace to gusset plate connections while maintaining its buckling resistance, alternative solutions consisting of incorporating ductile fuses within the brace members or their connections have been proposed. When ductile fuses are introduced in series with braces, they are designed to yield in tension at a lower force than the brace tensile strength [5–7]. Similarly, the bracing system of CBF structures may be preserved to behave elastically when the brace's gusset plate connections are replaced by dissipative connections, such as pin connections [8] or cast steel yielding fuse connections [9]. Thus, by incorporating fuses in the brace–frame connections, the fundamental period of the building elongates, the seismic demand quantified in term of design base shear decreases, while braces are protected against buckling [10].

The purpose of this paper is to illustrate the behaviour of dissipative single- and double-pin connections through numerical modelling and parametric studies by using the OpenSees framework [11]. The proposed design methodology and numerical models are validated by means of results obtained from existing experimental tests. The innovative double-pin connection with pins displaced in-parallel and in-line, proposed herein, has large redundancy and is recommended in design.

2. Dissipative pin connections

The single-pin fuse integrated in brace connection was initially proposed and experimentally tested in the frame of the European INERD

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project [12]. The brace-column pin connection consists of two outer-plates welded or bolted to column flanges, two inner-plates welded to the brace and a rectangular pin member with rounded corners running through the four plates. As illustrated in Fig. 1a, the configuration of pin device depends on the size and depth of the CBF column's cross-section that governs the pin's length, L_{pin}, while the size of the pin member depends on the probable compressive resistance of the connected brace, C_u, and the distance between the inner-plates (L_{pin}-$2a$). As illustrated in Fig. 1b, parameter a is the distance between the outer-plate and the centerline of the inner-plate. The pin element is proportioned to yield in flexure under a force equating 60% C_u of the attached hollow structural section brace, HSS [10].

In this study, the behaviour of single-pin device is analysed through numerical modelling, developed in the OpenSees framework version 2.2.0 [11]. Then, the single-pin connection model is calibrated against results obtained from experimental tests, conducted at Technical University of Lisbon, Portugal [12]. When large axial forces need to be transferred from braces to CBF columns through connections, the available sizes of single-pin member may not be sufficient. To overcome this limit, the authors proposed an innovative double-pin connection with pins displaced either in-parallel or in-line, as illustrated in Fig. 2. By employing the same design approach as that used for the single-pin device, the proposed double-pin connection is analysed in both configurations through theoretical and numerical modelling with the aim of sizing the specimens and preparing the upcoming experimental tests.

3. Design and behaviour of single-pin connection device

To validate the design method for the single-pin connection device, two numerical models are employed and defined as follows: the theoretical beam model and the OpenSees beam model. Regarding the theoretical beam model, the same approach considered by Vayas and Thanopoulos [13] and refined by Tirca et al. [8] is used to size the pin cross-section and the connection's components. Then, the theoretical beam model was replicated in the OpenSees framework with the aim of investigating the stress versus strain development along the pin cross-section, as well as the length of plastic zone resulted under incremental static loading up to failure. By using data from both theoretical and OpenSees beam models, the authors replicate two experimental tests conducted at the Technical University of Lisbon under quasi-static displacement loading. The calibration of the model is validated when both the experimental and simulated models match in terms of hysteresis loops generated from plotting the force versus displacement and the cumulative dissipated energy.

3.1. Theoretical beam model

The behaviour of the single-pin device in terms of its capacity to dissipate energy under cyclic loading is influenced by the following parameters: the length of the pin, L_{pin}, its cross-sectional shape and size, as well as the distance between the inner-plates (L_{pin}-$2a$). As illustrated in Fig. 1, the axial force developed in the brace, P, is transferred to the pin through the two inner-plates as uniformly distributed loads which act along the thickness of the plates. For simplicity, the pin is considered to behave as a four-point loaded beam, where the concentrated load $P/2$ is the resultant of the uniformly distributed force, as is shown in Fig. 3a. When the yielding moment $M_y = W_y F_y$ is reached, the pin starts to yield in bending under the applied point load $P_y/2$, where $P_y/2 = M_y/a$. By employing Hooke's law, yielding of pin is initiated when the maximum normal strain that is developed at the top and bottom fiber of the rectangular pin's cross-section ($b_p \, x \, h_p$) is $\varepsilon_y = F_y/E$, where b_p and h_p are the dimensions of pin's cross-section and E is the modulus of elasticity. Thus, the applied $P_y/2$ loads bent the simply supported beam in single curvature as illustrated in Fig. 3c. It is noted that 1 mm clearance was provided between the pin and the outer-plate hole [14], which meets the requirements of the current standard [1]. The deflection required to produce material's yielding at the pin's mid-span is $\delta_y = \rho(1 - \cos(L_{pin}/2\rho))$, where ρ is the radius of curvature and the curvature is defined as $k_y = 1/\rho = 2\varepsilon_y/h_p$. However, the strain corresponding to the static yield stress may be two to five times the yield strain ε_y [15]. At this stage, the strain considered to compute the static yield stress, ε_I, is expressed as: $\varepsilon_I = 1.5\varepsilon_y$ and the corresponding curvature becomes $k_I = 2(1.5\varepsilon_y)/h_p$ and $\rho_I = h_p/(3\varepsilon_y)$. The maximum deflection computed at the pin's mid-span is given by Eq. (1) and the maximum deflection under the point of loading may be obtained by multiplying δ_y with the ratio $2a/L_{pin}$. Although the provided deflection equation applies rigorously for the case of pure bending, as is the segment between inner-plates, the assumption that cross-sections remain plane and perpendicular to the deformed axis leads to expressions for normal strain ε and stress σ that are quite accurate in the elastic range even in the case of non-uniform bending ($dM/dx = V(x) \neq 0$), as are the segments between outer- and inner-plate [16]. The yielding moment, $M_y = W_y F_y$, is reached under the application of two $P_y/2$ loads that are defined in accordance with Eq. (2).

$$\delta_y = \delta_I = \left(h_p/3\varepsilon_y\right)\left(1 - \cos\left(1.5 L_{pin}\varepsilon_y/h_p\right)\right) \quad (1)$$

$$P_I = P_y = 2M_y/a \quad (2)$$

For a rectangular cross-section, the ratio between the plastic moment M_p and M_y equates the shape factor given by $W_y/W_p = 1.5$. After the attainment of M_y, some clamping forces start developing at the pin's ends and in consequence the boundary conditions gradually allow the development of end bending moment (Fig. 3b). By equating the external work, $P\delta/2 = P(\varphi a)/2$, with the internal work, $(M_1 + M_2)\varphi$, where φ is the rotation as illustrated in Fig. 3c, the magnitude of the ultimate load carried by the beam, P_{II}, is given in Eq. (3). It is estimated that the ultimate flexural capacity of the pin member, M_u, is computed as: $M_u = W_p F_u$, where F_u is the steel ultimate strength. Under the two-point loads $P_u/2$, the ultimate strain, ε_{II}, is approximated as being equal to $\varepsilon_{II} = 50\varepsilon_y = 0.1$ and the corresponding curvature is $k_{II} = 2\varepsilon_{II}/h_p = 0.2/h_p$. The value of the ultimate plastic rotation, φ_u,

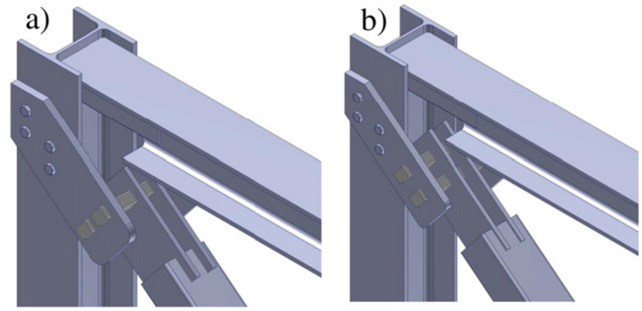

Fig. 2. Dissipative double-pin connections: a) pins in-paralel; b) pins in-line.

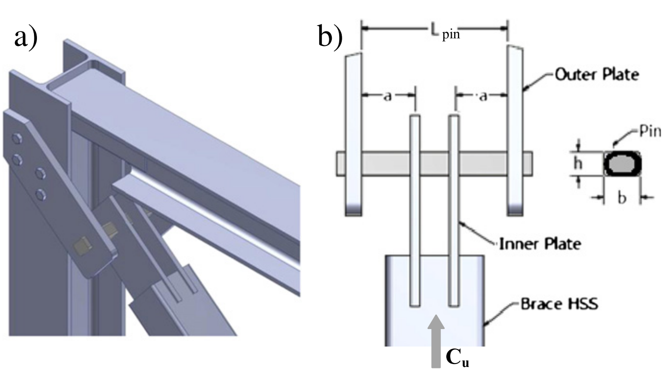

Fig. 1. Dissipative single-pin connection: a) 3-D view; b) detail.