DETAILED SEISMIC MODELLING OF PORTAL RC FRAMES WITH PRECAST BEAMS CONNECTED BY POCKET JOINTS AT THE UPPER COLUMN ENDS

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ABSTRACT:

Past research works and post-earthquake field missions have revealed the vulnerability of a number of portal RC frames made of precast RC members using pocket connections to join beams and columns. Typically the beam-column joint in these frames is assumed for analysis purposes as a simple pinned joint so that relative translations between beam and column ends are neglected while allowing the free rotation of these ends; however this assumption cannot always be justified, particularly when slippage at the beam seat can occur or when the beam ends make contact with the back walls of the pocket connection as a result of slippage and relative rotations of the beam with respect to the column. Furthermore, modelling the above connections as pinned joints does not allow the assessment of beam seat loss as a possible cause of collapse. This article introduces a new approach to model the nonlinear response of the above joints accounting for the kinematics of the problem as well as material nonlinearities. To that effect the joint is modelled by an assembly of gap elements, frictional joints, rigid links and nonlinear fibre elements. A series of nonlinear inelastic time-history seismic analyses of precast RC portal frames of existing industrial buildings are included in the study. Results demonstrate the ability of the new model to predict both the frictional sliding at the beam seat region and the pounding between the beam and the back wall of the pocket connections.

KEYWORDS: seismic response of precast portal RC frames, beam-column pocket connection, seat loss.

1. INTRODUCTION

A portal frame made of precast RC members (PFPRC) is a common structural form present in many industrial buildings around the world. A number of authors have exposed the vulnerability of some of these frames when subject to seismic motion (*e.g.* Sezen *et al.*, 2000; Posada and Wood, 2002; Senel and Palanci, 2013; Liberatore and Sorrentino, 2013; Bournas *et al.*, 2013; Belleri *et al.*, 2015). Hence, it is important to develop robust models to assess the seismic response of these structures in order to decide, for instance, if an existing PFPRC is vulnerable to collapse and/or if seismic upgrading is required. Figure 1 shows and example of a PFPRC with pocket connections used to join the beam and columns. The portal frames of this type of construction are primarily designed to resist seismic action in a direction parallel to the longitudinal axes of the beams, which seat at the pocket connections. Under gravity loading beams can be assumed as simply supported. Under seismic loading a simple model of the structure assumes that the beam-column joints of the PFPRC are pinned joints. The use of this simple joint model may be appropriate only under mild earthquakes. For this scenario it can be argued that inside the pocket connection enough horizontal friction force is developed at the beam seat to prevent any sliding of the beam, and gaps between the ‘walls’ of the pocket and the beam do not close entirely. Under these conditions free rotations are possible and the connection at the pocket behaves as a simple pinned joint. However under a relevant seismic event significant frictional slippage between the beam and the columns could happen, and gaps inside the pocket could also close. These phenomena invalidate the simple joint model and hence the pocket connection can no longer be assumed as a pinned joint.

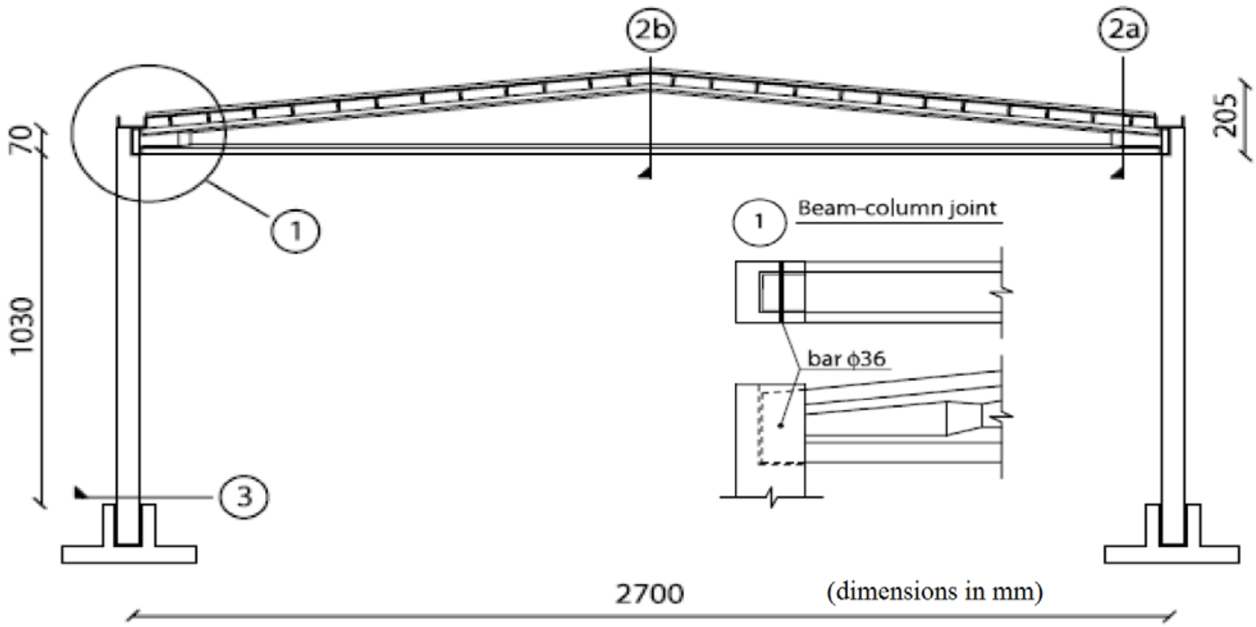


Figure 1. Portal frame made of precast RC members
(adapted from Martinelli and Mulas, 2010 in Al-Mamoori, 2019)

1.1. Objectives and scope

In view of the above limitations of the simple joint model, the main objective of this work is to introduce a more robust model of the beam-column pocket connection. In this new model deformation and strength mechanisms of the connection account for potential frictional slippage at the beam seat, as well as, for the reaction forces between the pocket joint and the beam every time the gap between these two elements close. This new model is referred here to as the detailed model of the pocket joint and it is applied in the modelling of a typical PFPRC subject to horizontal seismic action in a direction parallel to the longitudinal axis of the beam. The model is validated by a number of time-history analyses under earthquake ground motion (EGM).

2. IMPLEMENTATION OF A DETAILED MODEL OF A POCKET CONNECTION

Figure 2 shows an example of the geometrical details of a typical pocket connection under study. The structure corresponds to an industrial building previously studied by Martinelli and Mulas (2010) and by Al-Mamoori (2019). Both beam ends seat inside pockets located at the upper ends of the columns; a pocket element is delimited by a ‘back wall’ and two ‘side walls’. Depending on the EGM two kinematic phenomena may occur. First, every time the gap between the beam and the back wall closes additional mechanisms of strength and stiffness are triggered. Second, sliding friction across the beam seat results in relative displacements between the beam and the column, and in extreme cases large displacements in a direction away from the back wall may lead to building collapse due to the beam losing its seat.

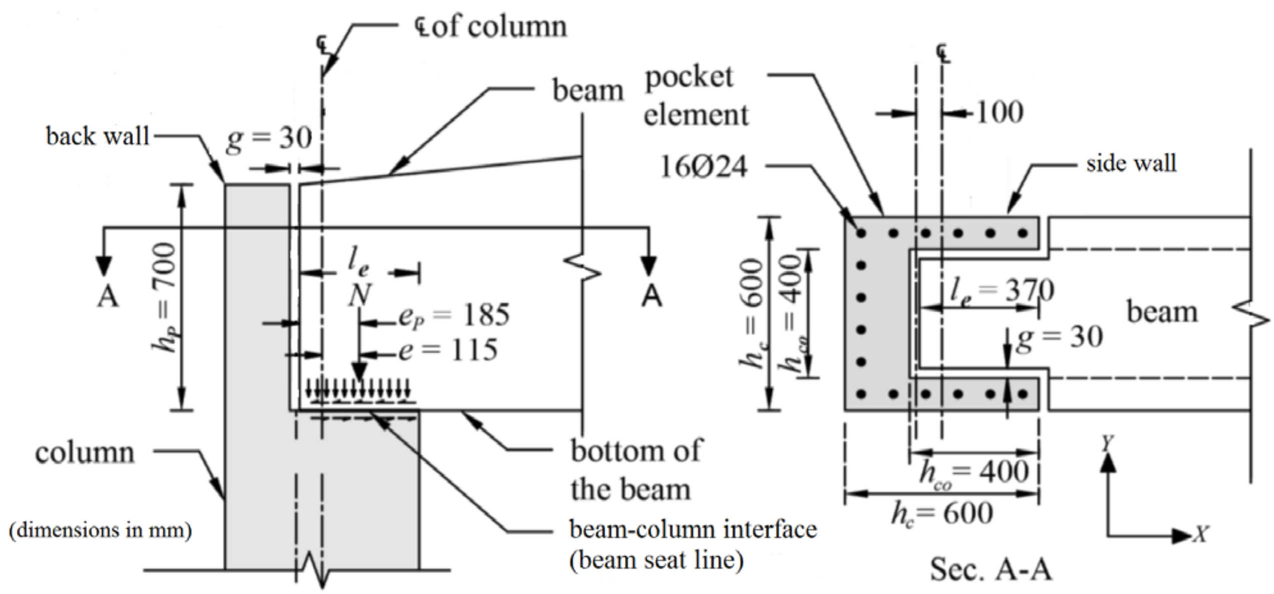


Figure 2. Geometrical details of a beam-column pocket connection.

2.1. Characterization of the detailed model

The above kinematic phenomena: pounding between the beam and the back wall, as well as, the sliding friction of the beam along its seat will be accounted for in the detailed model. In the interest of simplicity the influence of any steel dowels (such as the steel bar Φ36 indicated in Figure 1) is assumed to be negligible as they have been placed mainly to facilitate the assembly of the precast members. Figure 3 shows a schematic diagram of the proposed detailed model of the beam-column pocket connection. This model can be built in a nonlinear FE program, such as SAP2000 (Computers and Structures, 2015), which was used for all the analyses reported here.

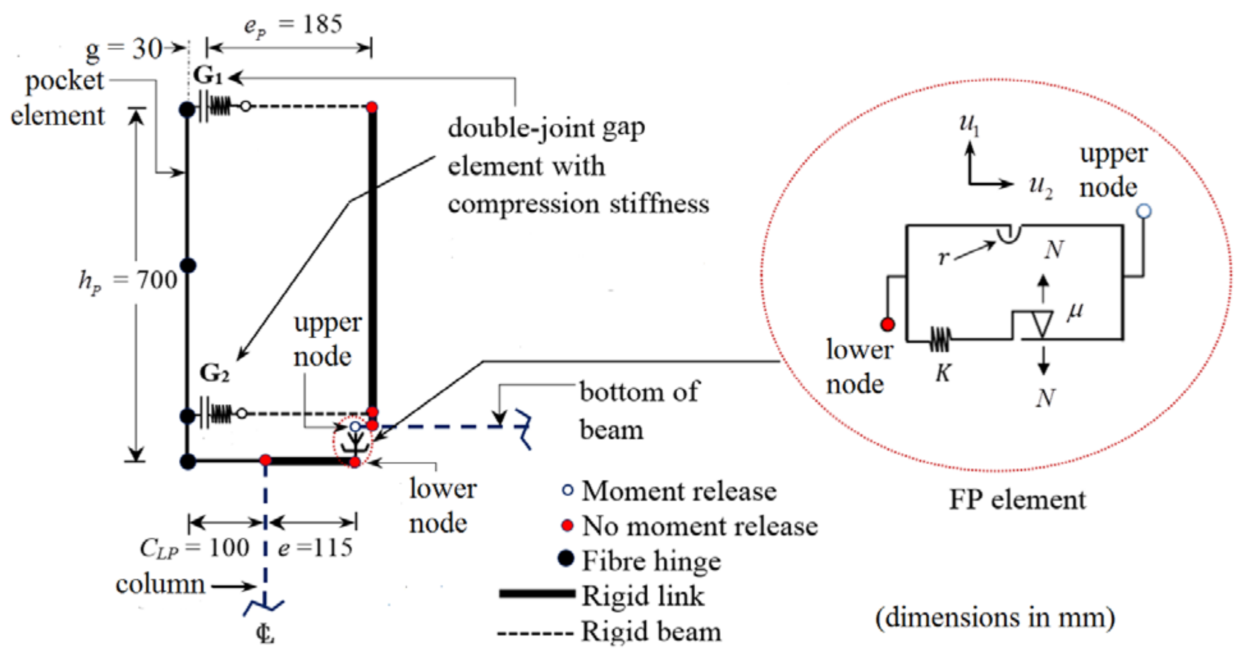


Figure 3. FE mesh of the proposed detailed model of a RC beam-column pocket connection.

The model consists primarily of a pocket element, gap elements, a horizontal friction element, pinned joints and rigid links. The pocket element (see its U-shape cross section in Figure 2) is modelled by an assembly of 3 inelastic RC fibre elements. The potential pounding between the beam and the back wall is modelled by the compression-only gap elements G_1 & G_2 set to have a high compression stiffness (in the order of 10 times the lateral stiffness of the pocket element). The frictional interaction at the beam seat region is modelled using a fictitious friction-pendulum isolator (FP element) with properties described in more detail below.

2.1.1 Modelling of friction forces

The FP element has the degrees of freedom u_1, u_2 shown in Figure 3, and can model a sliding force between two dry surfaces in the u_2 direction. The friction forces of the element are directly proportional to the compressive force acting along the u_1 direction (the element cannot carry a tensile force). FP elements are conventionally used to model base isolation systems that relay on friction damping and small amplitude pendulum motion. However, in this work the radius of the FP element was set to zero so that the element was able to model the frictional behaviour of a flat surface where beam and columns interact (*i.e.* the beam seat region). The normal force N resulting from the vertical reaction of the beam over the column affects the force resisted by the FE element and it is governed by a Coulomb friction model given by

$$F_f \leq \mu_s N \text{ if } V = 0 \tag{1}$$

$$F_f \leq \mu_k N sgn(V) \text{ if } V \neq 0 \tag{2}$$

Where F_f is the friction force tangential to the contact surface between the bodies in contact; μ_s and μ_k are the coefficients of static and kinetic friction respectively. The term $sgn(V)$ ensures that the friction force opposes the velocity of sliding V in the u_2 direction. It is assumed that at the area of contact between the beam and the column the integrity of concrete remains stable with no plastic deformation, wear or penetration produced by the normal force. Additionally, the hysteretic behaviour of the FP elements was assumed as elastic-perfectly plastic (*i.e.* if the normal force remains constant). The kinematic friction is estimated using the model of Constantinou *et al.* (1990) defined by

$$\mu_k = f_{max} - D_f\, e^{-\alpha V} \tag{3}$$

Where f_{max} is the friction coefficient at a so-called fast velocity; D_f is the difference between friction coefficients at fast velocity and at zero velocity, α is an interface constant that depends on the bearing pressure and the conditions of the contact surface.

3. APPLICATION EXAMPLE OF THE PROPOSED CONNECTION MODEL

This section presents analyses of three PFPRC frames with beam-column pocket connections modelled as described in the previous section. The connection dimensions are shown in Figure 2. The overall dimensions of the frames under study, which are the same for the three frames, are given in Figure 1. Each frame is differentiated by the gravity loading carried by the beam. Further details of the 2D frames and the FE mesh of nonlinear fibre elements used to model the beams and columns is given elsewhere (Al-Mamoori, 2019). Results of nonlinear time-history analyses under harmonic and earthquake ground motions are discussed below.

A dry conditions concrete-to-concrete friction coefficient $\mu_s = 0.57$ was used for the analyses (Rabbat and Russell, 1985; Engström, 1990); whereas the dynamic friction coefficient was estimated as $\mu_k = 0.30\mu_s$ (Mendez-Urquidez, 2009). A value of the interface constant α equal to 41 was taken as a good estimate to model concrete-to-concrete frictional sliding. Three levels of gravity loading acting on the beams were considered to assess the effect of the frictional response of the frame joints. These are referred to as light (LGL), moderate (MGL) and heavy (HGL) and have values of 0.5, 5.0 and 20.0kN/m, respectively. Eigenvalue analyses showed that the fundamental frequencies of the frames are 8.9rad/sec, 7.5rad/sec and 5.1rad/sec for the LGL, MGL and HGL, respectively.

3.1. Response under harmonic excitation

The above frames were subject to a fictitious harmonic ground motion of short duration (3.14 sec). This motion consists of the first two cycles of a sinusoidal ground acceleration time-history of amplitude PGA = 0.05g and frequency of excitation Ω = 4 rad/sec.

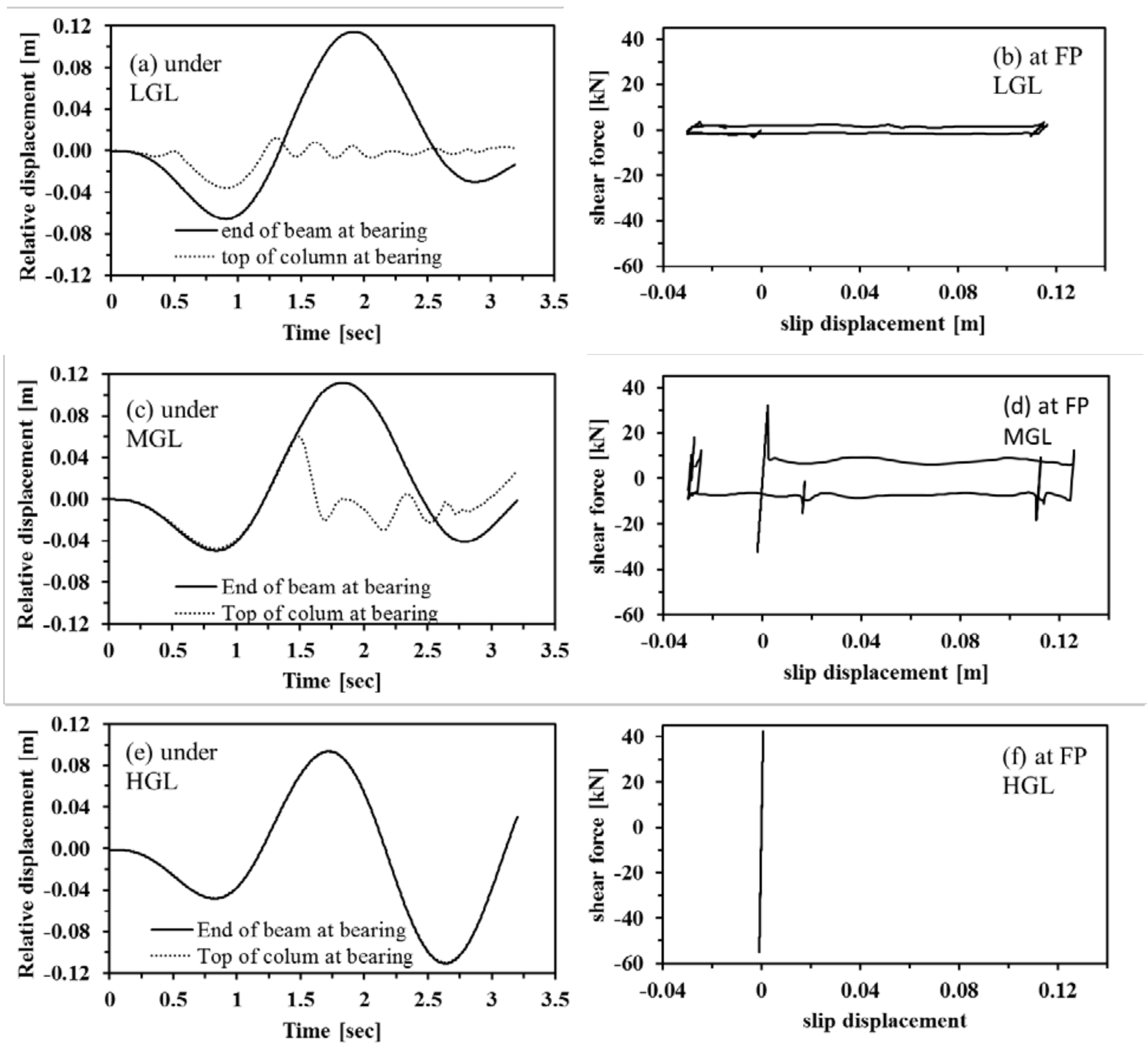
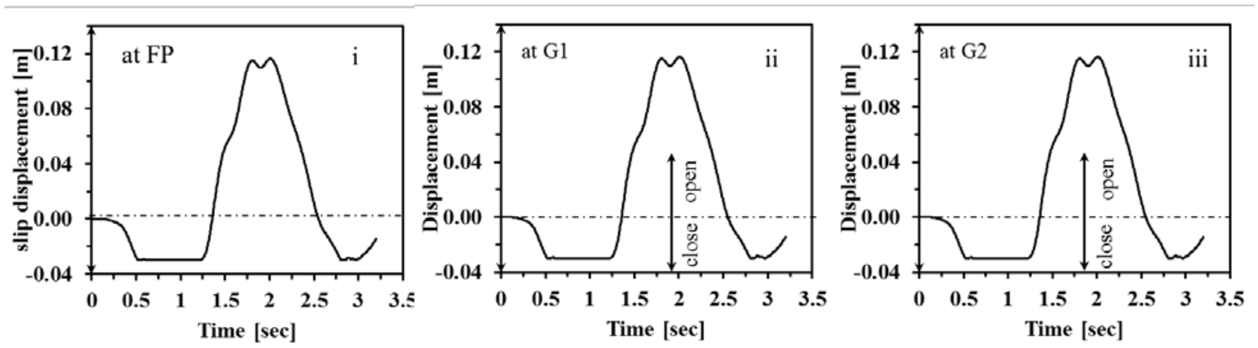
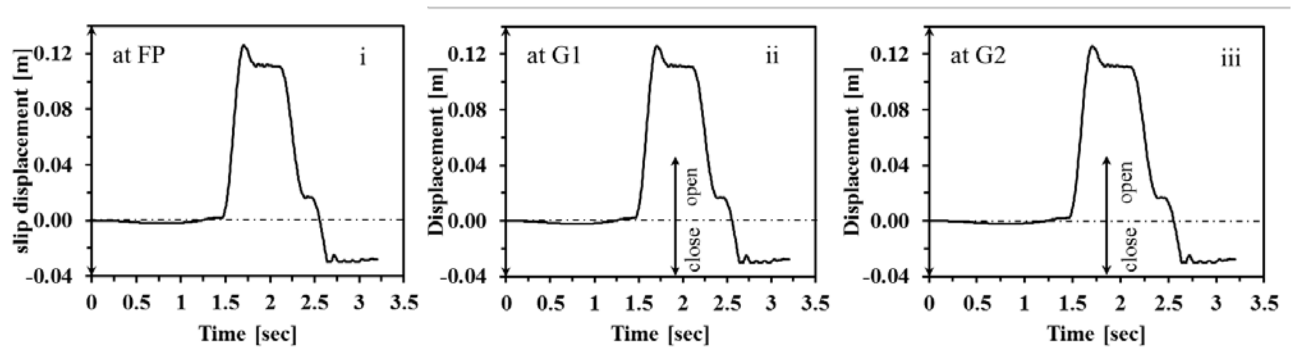


Figure 4. Displacement and hysteretic response at the beam seat interface for frames under harmonic excitation (results shown correspond to the left pocket connection).

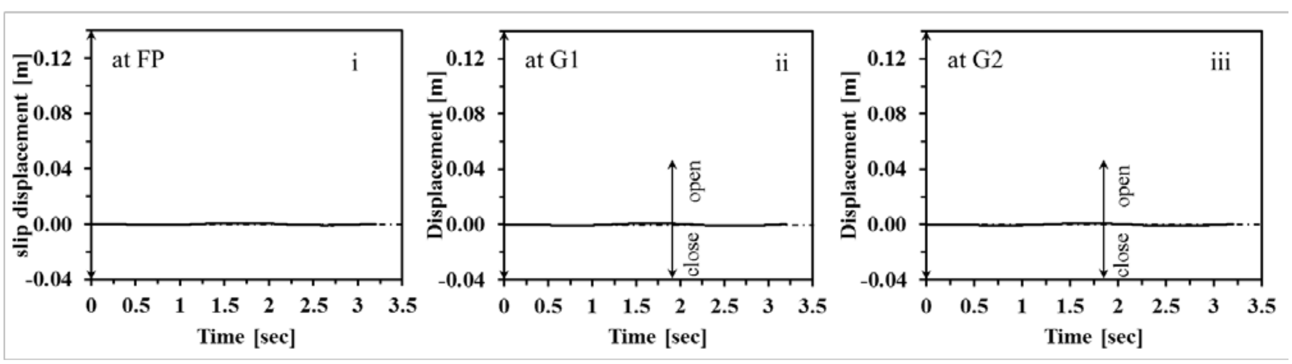
Figure 4 shows the response of the frames, firstly in terms of the lateral displacement of the beam end and the upper end of the column at the beam seat region, and secondly in terms of the hysteretic response predicted in the beam seat region. For the frame with HGL the friction force developed between the beam and the column is so high that slippage does not occur (*i.e.* the beam and the upper end of the column displace the same amount). On the other hand, for the lighter LGL and MGL cases Figures 4(a)-(d) indicate that significant slippage (with a maximum value of about 0.12 m) occurs within the pocket connection. Nevertheless, the beam does not lose its seat as the maximum slip displacement is smaller than the seat length of 0.37m indicated in Figure 2. The ability of the model to account for changes in the friction force at the beam seat interface as either a function of the velocity of sliding or the change in the column axial force is evident mainly in Figure 4(d).



(a) under LGL



(b) under MGL



(c) under HGL

Figure 5. Displacement response time-history of gap and FP elements under harmonic excitation
(results correspond to the left pocket connection).

Figure 5 shows the time-history of pounding between the beam end and the back wall of the pocket. As expected no pounding occurs under HGL since no slippage occurs as discussed above. On the other hand, for the LGL and the MGL the gap elements G_1 & G_2 (see Figure 3) close a number of times during the excitation, and the maximum closing displacement is equal to 0.03m as expected (*i.e.* the dimension of the gap *g* shown in Figures 2 & 3).

3.2. Response under earthquake ground motion

Figure 6 shows the seismic response of the frames under the action of the first 12sec of the well-known El Centro NS 1940 EGM. As in the case of harmonic excitation, the frame under HGL does not experience slippage at the beam seat region. On the other hand, frames under LGL and MGL both show significant slippage. The largest peak displacement and largest slippage values correspond to the frame with LGL. However, loss of beam seat is not predicted for any of the frames. As expected, more irregularities in the hysteresis loops of the FP elements are observed under EGM when slippage occurs (frames under LGL and MGL). The hysteretic plots show once more that the detailed model of the pocket connections captures the influence that both, the velocity of sliding and the variation of normal force in the beam seat have on the lateral force resisted by the connection.

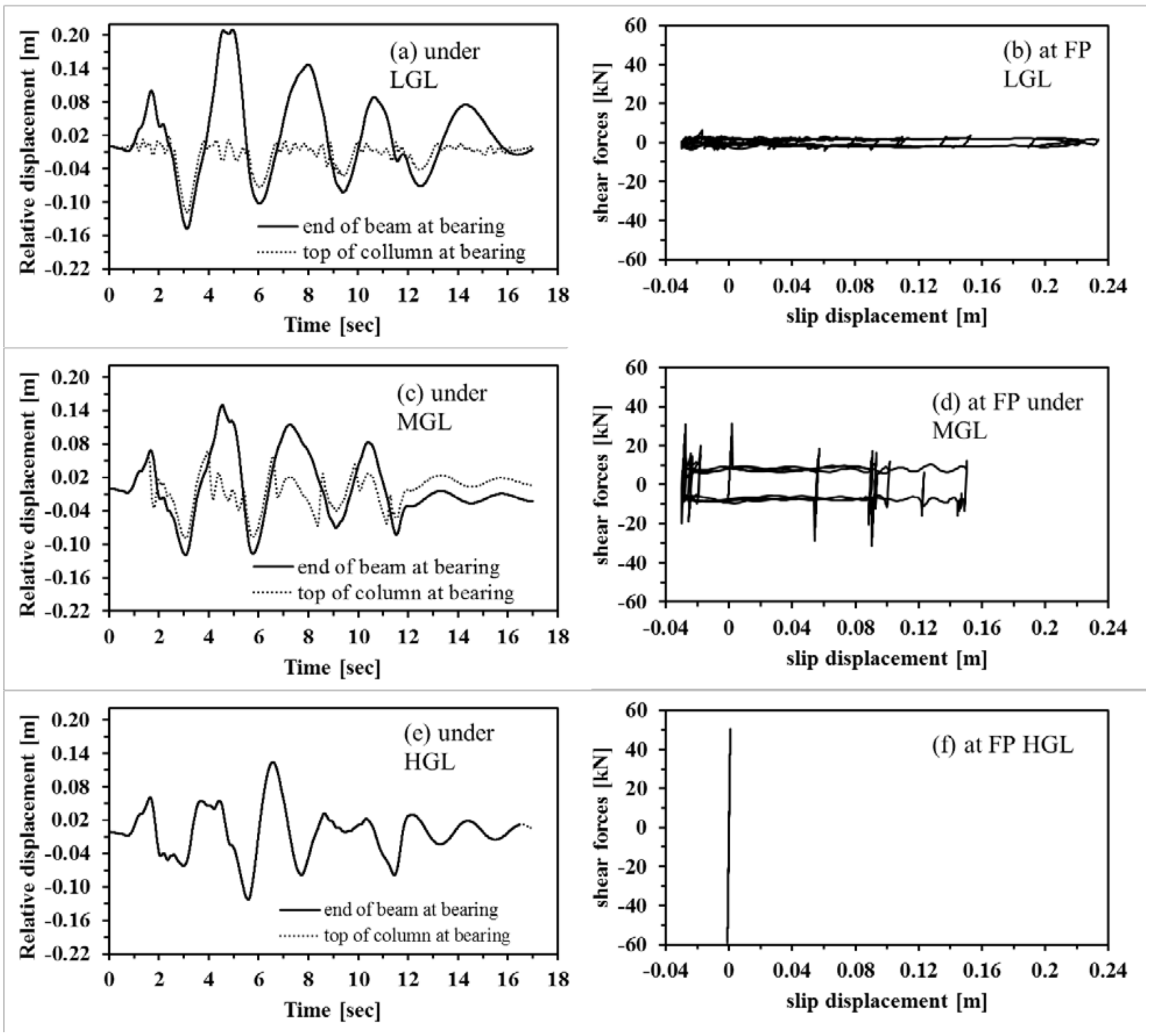
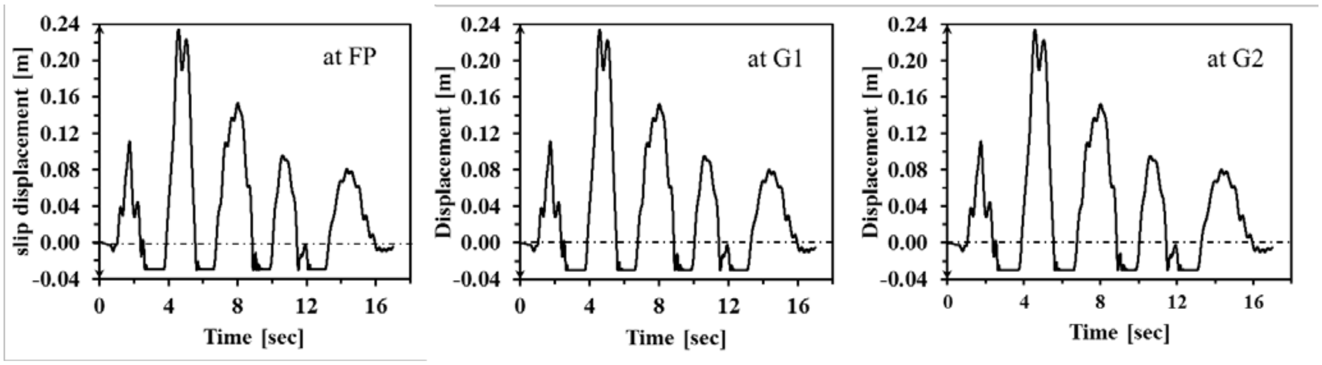
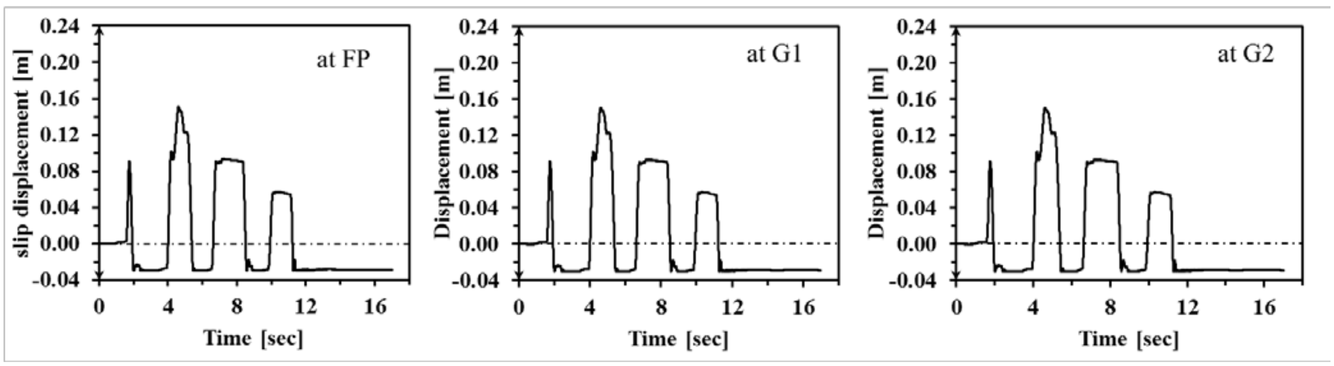


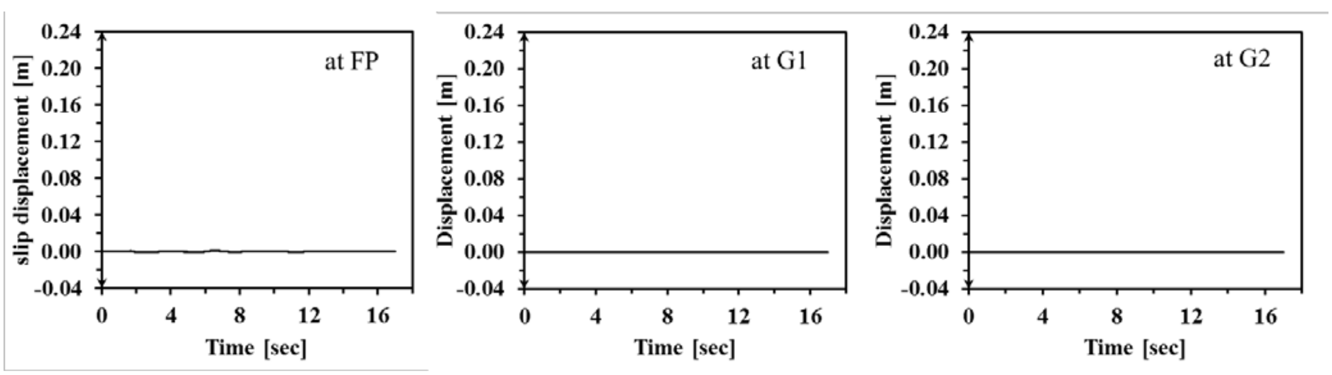
Figure 6. Displacement and hysteretic response at the beam seat interface under the action of El Centro NS 1940 EGM.



(a) under LGL



(b) under MGL



(c) under HGL

Figure 7. Displacement response time-history of gap and FP elements under the action of El Centro NS 1940 EGM.

Figure 7 shows the displacement time history of the gap and the FP elements. A similar trend as that for harmonic excitation is observed in the sense that no slippage and no gap closure occur for the frame under HGL. As expected, for the lighter load cases shown in Figures 7(a) and 7(b) the number of time intervals at which the gaps close increases when compared with the response under harmonic excitation. The maximum slip displacements at maximum gap opening are 0.23 and 0.15m for the LGL and the MGL, respectively; hence, the detailed model of the pocket connection predicts again that beam seat is not lost under the applied seismic input.

4. CONCLUDING REMARKS

This article has introduced a new model to predict the hysteretic response of a pocket beam-column connection commonly used in the precast construction of portal RC frames. Results showed that the implemented model is able to predict the potential beam slippage at the beam seat region as well as the pounding between the beam end and the back wall of the pocket connection. This model can be implemented in any robust FE analysis program that has the FE nonlinear joint/link elements used in the development of the proposed new model. In particular, the program must count with nonlinear link elements in which the lateral resistance of the joint can be coupled with the compressive-only force carried by the link. The implementation of the local mesh required to build the proposed model of the pocket connection may become cumbersome; however this issue may be solved by writing a code to automatically generate the FE mesh. Further validation of the proposed beam-column pocket connection model would require comparisons with shaking table test results of a large scale PFPRC. These dynamic tests however are beyond the scope of the work presented here.

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