Elongating plastic hinge element for nonlinear analysis of RC structures using OPENSEES

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ABSTRACT

During inelastic cyclic loading, the length of plastic hinges in reinforced concrete (RC) members increases irreversibly which significantly affects the seismic performance of RC structures. It is hence necessary for numerical and analytical models to capture elongation of hinges for reliable prediction of nonlinear cyclic response of RC structures. This paper reports the implementation of a new plastic hinge element capable of simulating elongation in the structural analysis program OPENSEES. The element is similar to the multi-spring plastic hinge element developed by Peng et al. (2013) and implemented in RUAUMOKO2D. The element includes two parallel rigid links interconnected by a number of axial springs modelled by cyclic stress-deformation behaviour of concrete and reinforcing bars and two diagonal springs, which collectively enable simulation of nonlinear cyclic response of RC members under combined axial, flexure and shear actions. As concrete models available in OPENSEES library are unable to capture the contact stress of cracked concrete, a new concrete hysteresis model is added to be used in the plastic hinge element. The new element can be used in both vertical and horizontal configurations (i.e. in beams as well as columns and walls). A preliminary verification is conducted by simulating a quasi-static cyclic loading test on a cantilever RC beam. Comparing the predicted and experimental results, it was found that the model was able to capture with reasonable accuracy the hysteretic response as well as the elongation of the beam throughout the cyclic loading history.

Keywords: Seismic performance, Reinforced concrete, Plastic hinge, Elongation, Nonlinear analysis, Lumped plasticity model

1 INTRODUCTION

Experimental evidences (Walker 2007, Liddell et al. 2000) have shown that the length of plastic hinges in reinforced concrete (RC) members increases between 2% to 5% of the member depth before reaching the strange degradation stage. Such elongation of beams in RC frames changes distribution of flexural and shear stresses inside the frame. Elongation of beam hinges also causes incompatibility between beams and the monolithically connected concrete floor slabs, which causes extensive cracking damage around the perimeter beams to floor interface and can even cause precast floor slabs to unseat from the frames. The effect of elongation hasn't been considered in most design codes, except for the recent amendment of the New Zealand Concrete Standard NZS3101 (2017).

Despite the importance of this phenomenon, common approaches of modelling of RC frames using lumped plasticity elements cannot capture the elongation of the plastic hinges. To compensate for the lack of numerical/analytical models, some empirical models have been proposed by researchers to estimate elongation (Fenwick and Megget 1993, Lee and Watanabe 2003, Mathew et al. 2004), but these models cannot be incorporated into time-history analysis. The fiber-based elongation models proposed by Douglas et al. (1996) and Lau et al. (2003) need to be calibrated with experimental results to be used in the numerical analysis. Another elongation model involving prestressed tendons for precast beams has been suggested by Kim et al. (2004) which is not applicable for flexural frames due to its very complicated nature. Overall, the fiber-based finite element models are suitable for numerical analysis and can capture elongation if reliable cyclic material models are used, but they impose high computational costs and hence are not preferred for analysing large structures like multi-storey buildings.

Peng et al. (2013) developed a macro-level plastic hinge element that can capture elongation of RC members and can be implemented in nonlinear time-history analysis of RC frames. This paper reports the key features of the plastic hinge element, its implementation in the structural analysis program OPENSEES, and its preliminary validation by simulating a quasi-static cyclic loading test of a RC beam.

2 ELONGATING PLASTIC HINGES

Large cyclic deformations in plastic hinges cause them to grow in length, and the elongation depends on different parameters such as axial load and loading history. Generally, plastic hinges in RC beams can be categorized either as unidirectional or reversing type. The relative magnitudes of gravity and seismic actions as well as the distribution of positive and negative longitudinal reinforcement determine the location and type of the plastic hinges likely to develop in RC beams. When the flexural moment caused by gravity is more dominant than seismic moments, unidirectional plastic hinges form at different locations during load reversals. On the other hand, where seismic moments are dominant, the maximum positive and negative flexural moments in a beam occur at the same locations (i.e. at the column faces), thereby forming reversing plastic hinges.

Peng et al. (2013) proposed an elongating plastic hinge element that has been implemented in the finite element analysis program RUAUMKO2D (Carr 2008). This element is composed of multiple springs representing the response of concrete and reinforcement within the section. A schematic representation of the element is shown in Fig. 1. The proposed element consists of 8 concrete springs as well as 2 steel springs representing the top and bottom reinforcement. The length of the plastic hinge element L_p is determined such that the diagonal compression struts are adequately inclined to balance the shear demand.

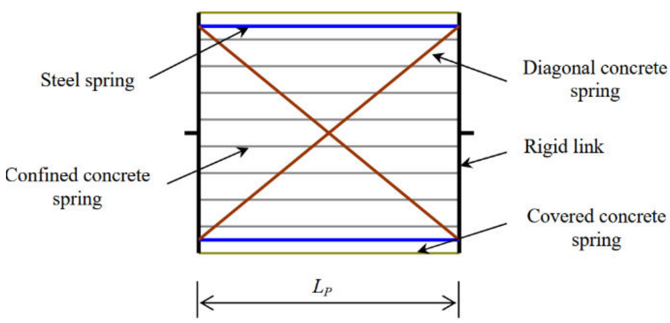
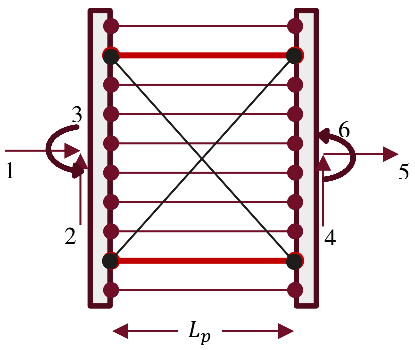


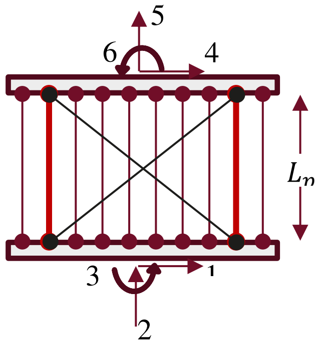
Fig. 1 - The schematic representation of the Peng et al. (2013) plastic hinge element

3 IMPLEMENTATION OF ELONGATING PLASTIC HINGES IN OPENSEES

Based on the plastic hinge element of Peng et al. (2013), a new element (named PDHinge) is coded for implementing in OPENSEES (McKenna 2011). The PDHinge element is a two-noded linear macro-element with axial, shear and rotational degrees of freedom at each node. The two nodes represent the centre of two parallel rigid links (of length equal to the depth of the member section), which are interconnected by a number of parallel axial springs and two diagonal springs. The element can be used in both horizontal and vertical orientations in beams or columns/walls, as shown in Fig.2. Contrary to the original plastic hinge element in RUAUMOKO, the number, width and thickness of the concrete springs may be determined by the users, which makes it usable for members of non-rectangular sections.



(a) horizontal orientation



(b) vertical orientation

Fig. 2 - The overview of the horizontal and vertical orientation of the new Plastic Hinge element 'PDHinge'

The element accounts for the effect of shear deformations on the strains of the longitudinal and diagonal springs. The deformed configuration of the element is used to calculate the geometric stiffness of the longitudinal springs to be used in the stiffness matrix. This renders the element avoid unnecessary computational instability, and enables the element to reliably predict large deformation response. Despite fetching the benefits of detailed section analysis using cyclic constitutive models of materials in fiber-based setting, the proposed macro element is more efficient and much faster in computation compared to modelling the multiple springs and the rigid links as separate individual elements which will create over 20 additional nodes at each end of a RC member.

3.1 Material models for the springs

The two springs representing tension and compression reinforcement are modelled with 'ReinforcingSteel' hysteresis, which can include the effect of buckling on their compressive stress-strain response. As the contact stress in the diagonal struts plays a crucial role in the stability of the element and also the convergence of the model in OPENSEES, concrete model by Maekawa et al. (2003) has been added to the OPENSEES library (called ConcreteMO). The ConcreteMO model was able to generate contact stress in concrete after cracking and produce reasonable amounts of axial force in the diagonal struts/springs. However, the original ConcreteMO model resulted in some convergence issues, which needed slight modification of the contact mechanism and modelling. Even though ConcreteMO may be used for the axial concrete springs, sensitivity analysis showed that the contact stress effect for concrete springs is insignificant. Therefore, 'ConcreteCM' and 'Concrete01' uniaxial materials are used for the confined and unconfined springs, respectively.

3.2 Verification of the new element

To verify the accuracy of the PDHinge element, the results of a cyclic experimental test on Beam2A conducted by Fenwick et al. (1981) are compared with the numerical analysis predictions. The geometric details of the beam section and the test configuration are shown in Fig. 3(a) and (b). Fig. 3(c) depicts the applied loading history where D_i is the vertical displacement corresponding to ductility i. Fig. 3(d) schematically shows the numerical model for one cantilever beam, which is represented by a PDHinge element adjacent to the support and an elastic beam element covering the remaining length of the beam.

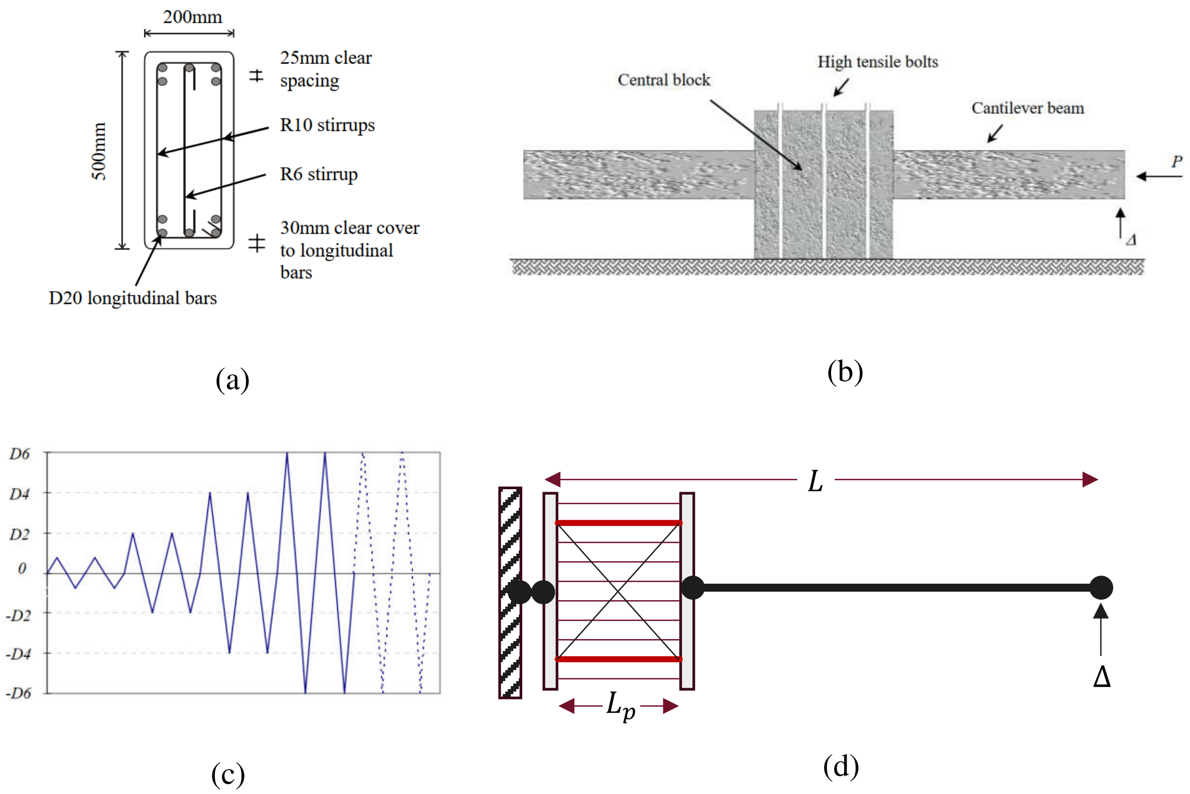
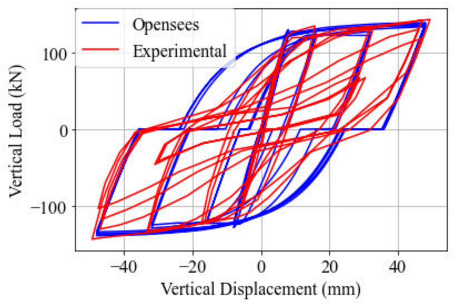
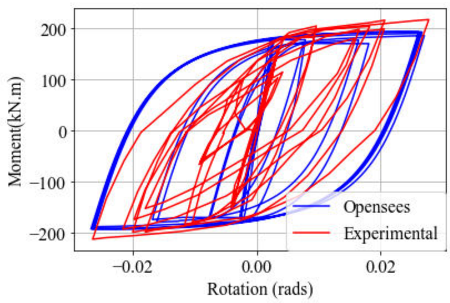


Fig. 3 -The characteristics of the Beam 2A test (a) section of beam 2A (b) test arrangement (c) loading history Peng et al.(2013) (d) schematic representation of the numerical model in OPENSEES

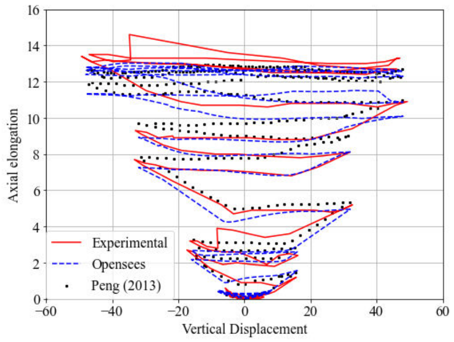
The hysteresis responses in terms of force-deformation and moment-rotation curves are shown in Figures 4(a) and (b). The axial elongation vs vertical displacement relationship is shown in Fig. 4(c) together with those measured in the test and predicted by Peng et al. (2013) using the hinge element in RUAUMOKO. The figures indicate that the plastic hinge model can predict the moment-rotation and force-drift responses of the beam with acceptable level of accuracy. While the pinching effect is tolerably captured during the initial cycles in Fig. 4(a), the mismatch (i.e. underestimation of pinching) is significant at larger displacement cycles. Also, it can be observed that the PDHinge element can accurately estimate the elongation up to the displacement cycles corresponding to ductility of 4 (i.e. D_4 cycle in Fig.3), and the first cycle of ductility 6. However, during the last three cycles of the analysis the elongation is underestimated by almost 15%. A sensitivity analysis was conducted to scrutinise the reasons, which suggested that a better agreement between experimental and numerical analysis may be achieved by adjusting the buckling related parameters in the model used for reinforcing steel. Hence, it is expected that the prediction will improve when a rebar model capable of reliably capturing the buckling effects is installed in OPENSEES.



(a)



(b)



(c)

Fig. 4 - The results of Beam 2A analysis (a) Force-displacement (b) Moment-rotation (c) Axial elongation vs applied displacement

4 CONCLUSIONS

This paper summarizes the implementation of a new plastic hinge element in OPENSEES (named PDHinge) for capturing the elongation of RC members under reversed cyclic loading, which can alter the distribution of the internal forces in RC frames. The element comprises of two rigid transverse links joined by multiple parallel axial springs and two diagonal springs to enable simulating the axial, flexural and shear response of the plastic hinge. As none of the available materials was capable of capturing the significant contact stress of cracked concrete required for stability of the plastic hinge element, a new uniaxial concrete material has been added to the OPENSEES library. The efficiency of the element is examined by simulating a quasi-static cyclic test on a cantilever RC beam. It was found that although the PDHinge element uses different material models for the concrete and steel springs than those originally used by Peng et al., it yields encouragingly acceptable predictions in comparison to the experimental results. The model could estimate the elongation of the beam with reasonable accuracy until the first cycle corresponding to ductility of 6, and the difference between the test results and model predictions thereafter was less than 15%. At the time of writing, further refinement and validation of the element is underway to improve its accuracy, versatility and reliability.

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