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SMRF Seismic Response: Unequal Beam Depths

Babak H. Mamamqani, Alimohammad Entezarmahdi

***Abstract*—**There are many researches on parameters affecting seismic behavior of steel moment frames. Great deal of these researches considers cover plate connections with or without haunch and direct beam to column connection for exterior columns. Also there are experimental results for interior connections with equal beam depth on both sides but not much research has been performed on the seismic behavior of joints with unequal beam depth. Based on previous experimental results, a series of companion analyses have been set up considering different beam height and connection detailing configuration to investigate the seismic behavior of the connections. Results of this study indicate that when the differences between beams height on both side increases, use of haunch connection system leads to significant improvement in the seismic response whereas other configurations did not provide satisfying results.

***Keywords*—**Analytical modeling, Haunch connection, Seismic design, Unequal beam depth.

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I. Introduction

NORTHRIDGE earthquake seriously damaged more than 150 steel moment resisting frame buildings of California [1], [2]. The performance of these buildings effectively questioned the building code that professional practice used before the earthquake for the seismic design and evaluation of steel moment frame structures. Very few experiments on the standard moment connection had been performed prior to the Northridge earthquake [2], [3], especially on the members of depth or sizes typically used in the building construction. In order to overcome the uncertainty involved in designing Steel moment Resisting Frames (SMRFs) the SAC joint venture conducted numerous tests to improve the cyclic behavior of connection modifying either weld detailing or geometry of connection [4]. The initial tests in SAC specimens were consisted of twelve specimens and performed on connections using standards of the pre-Northridge [5]. The performance of these connections was completely consistent with observations of connections damaged. All twelve tests failed in a sudden, brittle fashion after little or no significant yielding and little energy absorption was observed [5], [6]. Some tests were performed on "repaired" specimens [3] but the energy dissipation and ductility of these specimens varied and were not substantially superior to those of pre Northridge tests [7], [8]. The same modes of failure were observed in these "repaired" tests, so that significant yielding of the connection or development of a plastic hinge did not occur [9]. Much improved performances were achieved in the four tests that included the addition of a bottom hunch in the repair and establishing dog-bone system on the beam for controlling the place of hinging [10]-[13]. The design of the haunch intended to move the location of the plastic hinge away from face of the column, thereby protecting the critical complete penetration welds (CJP) at the face of the column from large inelastic demand. The concept of haunch design was to approximately limit the stress in the CJP welds to yield stress, when a plastic hinge began forming beyond the end of haunches [14]. Further improvement was also achieved in nonlinear behavior phase of connection [5]. The two cover plate connection tests performed quite well, with significant inelastic cycles. In each case the column joint panel zone experienced significant yielding in the early stages of loading [15]-[18], and then strain hardening occurred. Subsequent cycles indicated the development of local buckling of girder section beyond the cover plate, and the response was nearly similar to the double haunch repaired specimens. Significant energy dissipation occurred with 0.03 radian plastic rotation of cover on both cases. Some tests have been conducted on the effect of continuity plate on the seismic behavior of connections and moment frames. Popov et al. [14] performed a series of cyclic tests on cruciform subassemblagement, with and without continuity plates, to verify the design criteria for girder-to-column connections. The result of the test showed that, for two connections consisting of the same column and girder sizes, the inelastic girder rotation greatly increased when continuity plates were included in the connections [14]. Koufmann et al. [19] tested several fully welded girders to column connections under cyclic loading, they cited that fully welded connection which used electrodes with higher toughness values and fillet welded continuity plates can act in a ductile manner. Hosseini Hashemi and Ahmady Jazany [20]-[24] have conducted a series of experimental and analytical studies for interior column to investigate different connection detailing arrangements and showed that inclined continuity plate arrangement improve seismic performance of SMRF for unequal beam depths case. Ahmady Jazany et al. [25] continued the analytical research and implied that PZ shear strain values have a great dependency on connection detailing arrangements for unequal beam depth. Shadman Heidari et al. [26]-[28] also have performed an analytical parametric study to investigate the dominant fracture mode of interior column with unequal beam depth; they showed that straight continuity plates arrangement results in more strain accumulation at deep beam bottom flange due to unbalanced PZ shear strain in lower and upper PZ segments and this is the reason for fracture of the beam flanges. In addition, Ahmady Jazany and Golara [29] performed numerical analyses for exterior column to study the effect of connection type on PZ shear strain. They

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showed that PZ shear strain values are strongly affected by connection type. PZ with cover plate connection have more shear strain values compared to WUF and haunch connection systems [30]-[32]. As stated in this section, most of these tests have been performed on an exterior column or interior column with equal beams on both sides, but unequal beams for interior joints has not been considered. This research investigates the effects of unequal beams depth and some different possible connection and continuity plate arrangements on seismic performance of SMRF for unequal beam depth.

II. Validation of Analytical Model

Federal management agency [33] of America has summarized some of investigations regarding welded connection for exterior and interior columns with equal beam depth including: Popov [34], Whittaker [35], Blondet [36], Shuey [37]. To compare the seismic behavior of different connection arrangements Hosseini Hashemi and Ahmady Jazany [21] used FEM models with different arrangement of continuity plates and types of connections besides six analytical model of the tests [21]-[23] to verify the FEM modeling. The connection detailing arrangements consisted of 1) connection configuration: cover plate and flange plate connection for deep beam and shallow beam and haunch connection system 2) continuity plate arrangement including inclined and straight continuity plate formation. Combination of these configurations made different connection detailing arrangements [20]. Material properties of these models had kinematic behavior with strain hardening in nonlinear phase to predict the actual properties of the material [21]. The stress-strain relation for all connection components except for the bolts was modeled using a three-linear constitutive model. The yield stress and ultimate stress of weld were assumed to be based on nominal properties of E6013 (AWS A5.20)[6]. Modulus of elasticity and Poisson's ratio were considered respectively as $2.1\times10^6\ kg/cm^2$ and 0.3. Experimental and analytical cyclic response for the test specimen U1-FUW3 of this ensemble, which consisted of a beam to column assemblage with unequal beam depth with haunch connection system and flange plates connection on the shallow and deep beams, are shown in Fig. 1. Considering this figure, there is a good agreement between experimental and analytical results. Differences between the numerical simulation and test result may be due to several causes like numerical modeling simplification, test specimen defect or residual stress. In addition, the material properties, which are used in FEM, are from average, but in reality steel is not a homogenous material and amount of every coupon test result could affect the actual result. Overall, the results show good agreement with test data.

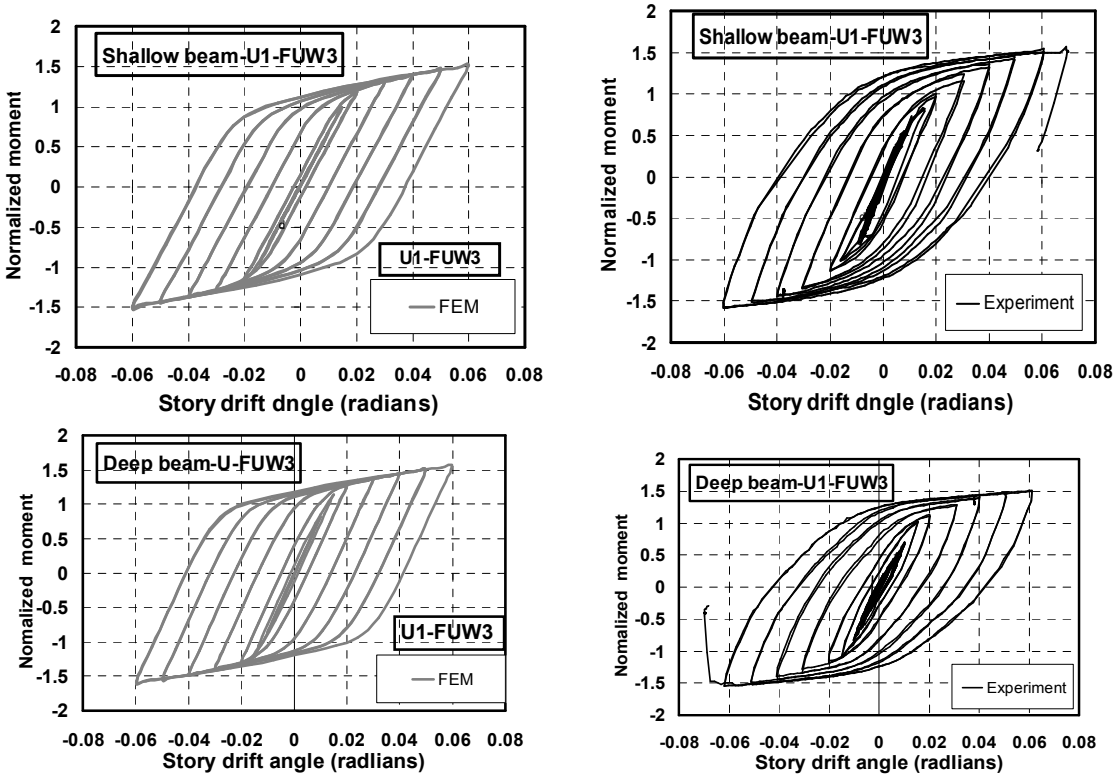
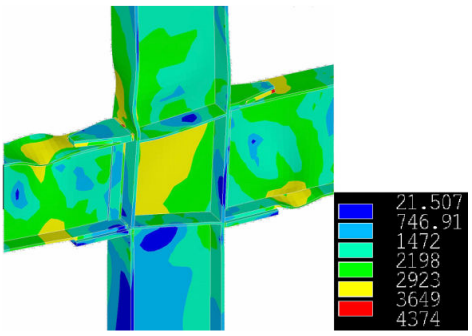


Fig. 1 Experimental and analytical model for the deep and shallow beams for test specimens U1-FUW3

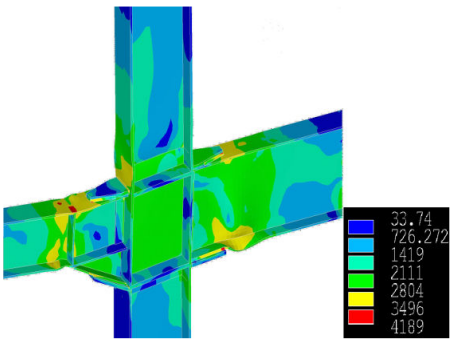
Figs. 2 (a) and (b) show the Von- Mises stress for reference models U1-FUW1 and U1-FUW3. To simulate the boundary condition of the experiment, the end of beam was restrained from outward motion in FE models. Furthermore, because of existence of lateral bracing system in real model on the flange of beam in actual test, some points on the flange of the model

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due to distance from column face were also restrained. Since there was no information about the situation of bolt regarding pre-tension or ordinary twisting of bolt, it is considered as ordinary condition which would not permit shear tab to slip outward the plane of web. The displacement control loading procedure was in accordance to SAC test protocol [6].



(a) Von-Mises stress distributions for analytical model U1-FUW1 based on experiments[20]



(b) Von- Mises stress distributions for analytical model U1-FUW3 based on the experiments[20]

Fig. 2 Von- Mises stress distributions view of the analytical models

III. Introducing Analytical Models

Three groups of analytical models with different column depth have been included in this study. In each group, two definite beam height differences were considered, and in each height difference, the panel zone thickness was calculated based on strength design concept (IBC2000) [37]. Four connection detailing arrangements were also considered for analytical models with unequal beam depth which consisted of: (1) model with straight continuity plate and (2) inclined continuity plates, (3) the model with straight continuity plate and model with one sided haunches, (4) the models with straight continuity plate and one-sided haunches as shown in Fig. 3. Considering four connection detailing arrangements with three column and two beam depths (beam 50-beam 40) and (beam 50-beam30) on sides; totally 24 analytical models for parametric analyses has been created. SOLID45 [38] element of ANSYS finite element program was used for creating models of parametric analyses with the same mesh sizes as the reference models which was used for verification. All models were designed according to IBC2000 [39] and AISC-2005 [40]. Geometric specification of the beams and columns of the analytical models are summarized in Tables I and II. The naming convention of the analytical model consists of two parts and it is illustrated in the format of "Type X-Y"; where X is beam to column configuration as presented in Table III and Y presents connection detailing arrangement as shown in Fig. 3. It is worth mentioning that strong column weak beam ratio in type 1-Y to type 6-Y are: 1.12, 1.05, 1.3, 1.21, 1.6, and 1.45 respectively.

TABLE I
Geometric Specification of Column

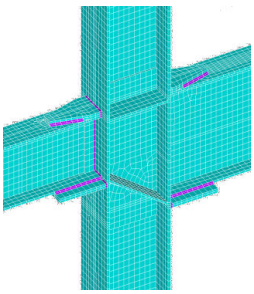
Type of columns	web height (cm)	flange width (cm)	Thickness of web(cm)	Thickness of flanges (cm)
column35	35	25	1	1.5
column 45	45	20	1.2	1.5
Coloumn55	55	20	1.2	1.5

TABLE II
Geometric Specification of Beams

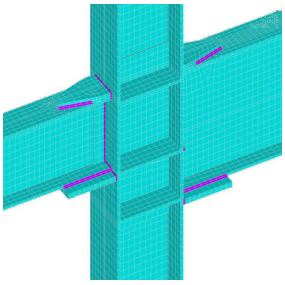
Type of beams	web height (cm)	flange width (cm)	Thickness of web(cm)	Thickness of flanges(cm)
Beam 50	50	15	1	1
Beam 40	40	15	1	1
Beam 30	30	15	1	1

TABLE III
Beam to Column Configuration

	Beam to column configuration		
X	Column size (cm)	Deep beam(cm)	Shallow beam(cm)
1	35	50	40
2	35	50	30
3	45	50	40
4	45	50	30
5	55	50	40
6	55	50	30



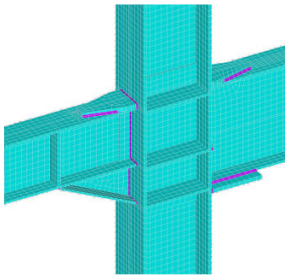
(a) Inclined continuity plate (Y=1)



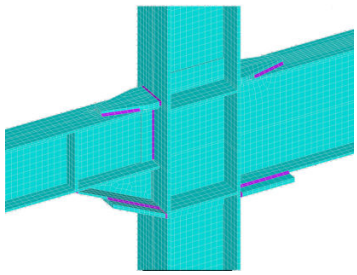
(b) Straight continuity plate (Y=2)

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(c) One sided haunch connection (Y=3)

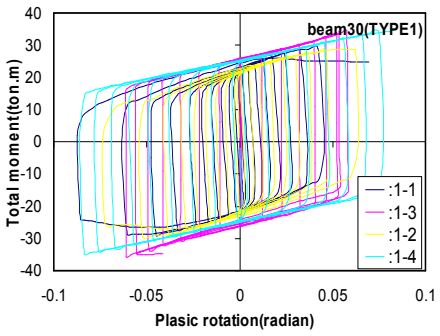


(d) One sided haunch with inclined cover plate (Y=4)

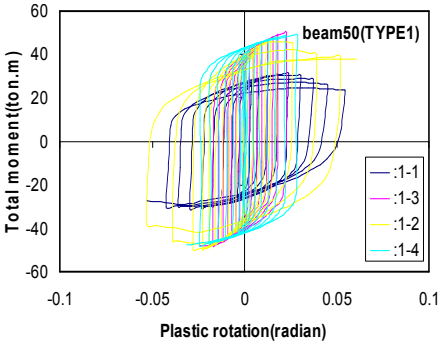
Fig. 3 Connection detailing Configuration (a) to (d)

IV. Numerical Results

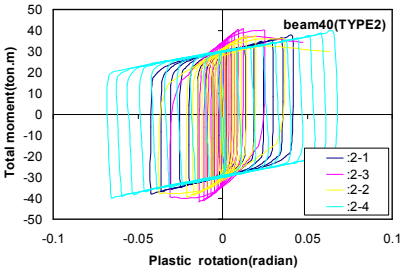
Static nonlinear analysis, considering the buckling and large displacements effects has been carried out on 24 described models. Figs. 4 (a) to (l) show deep (50) and shallow beams (40/30) cyclic response for different analytical models. It is evident that when the difference between beams increases, i.e. beam arrangement (50-30), types 2-Y, and types 6-Y show more strength in comparison with others. However Type 1-1 shows more ductile behavior; furthermore in type 1-2, Type 3-2, Type 5-2, beam 50cm has more strength, but sallow beam and deep beams of Type 1-2, Type 3-2,Type 5-2 have more ductile behavior. Regarding this figure, Types 5-3, 6-3, 4-3, 3-3, Type 6-4, 5-4, 4-4 and 3-4, globally have more strength than others in all beams configurations. Also type 6-4 has more ultimate strength for the deep beam compared to the corresponding values for other different configurations.



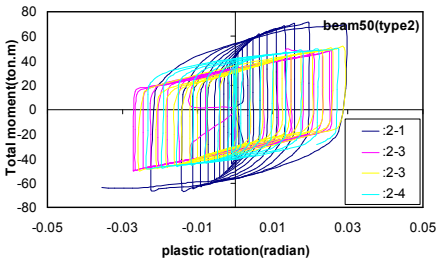
(a)



(b)



(c)



(d)

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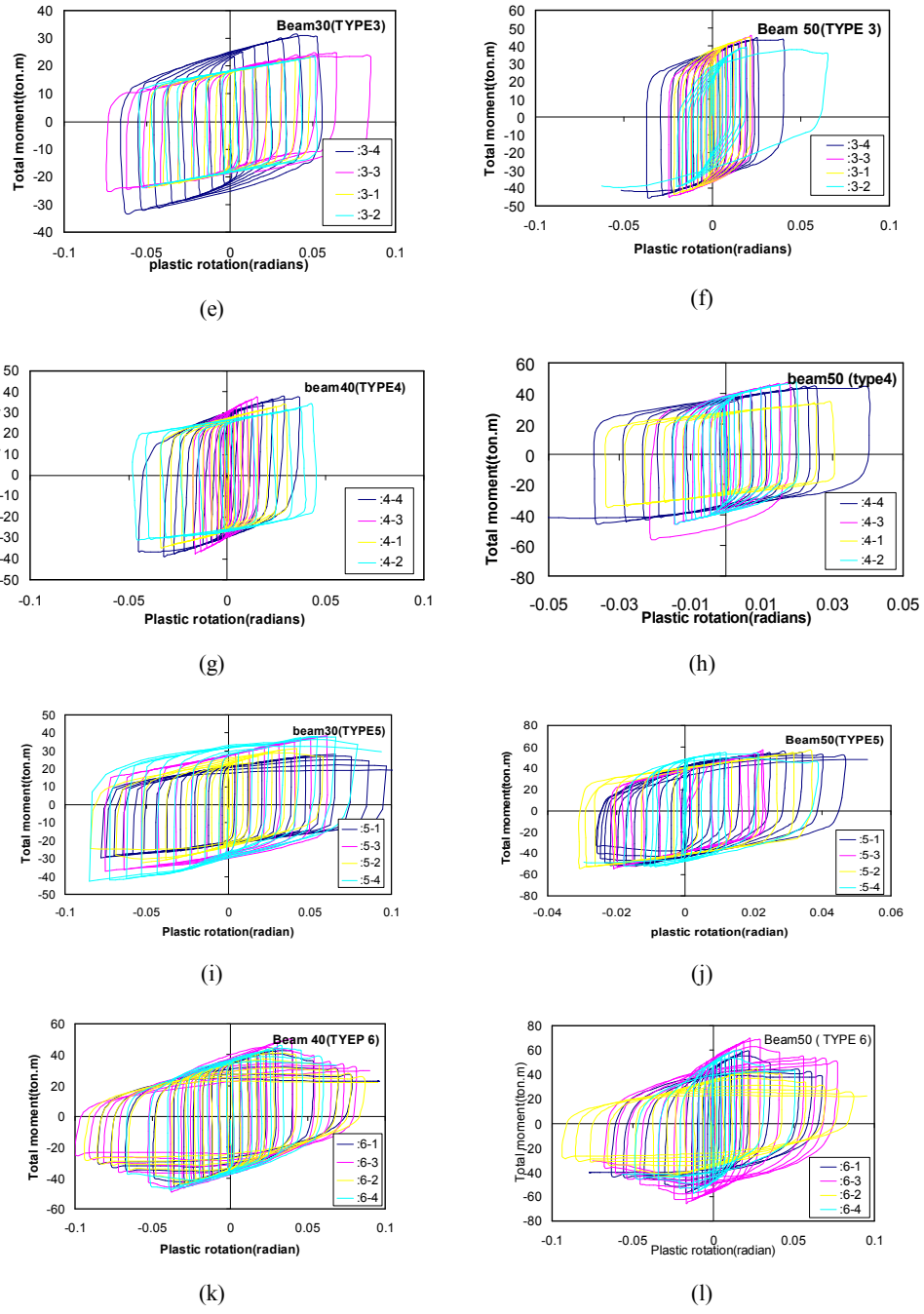


Fig. 4 Cyclic response of analytical models

V. Conclusion

Concerning this research, following conclusions can be made:

1. When strong column-weak beam ratio of analytical models are within 1 to 1.1 (type 1-y), in case of small differences of beams height, inclined continuity plate (arrangement 1) establishes better seismic behavior in deeper beam.
2. For the analytical models with strong column-weak beam ratio of 1 (in type1-y), in case of larger differences in beams height (beam 50 and 30), all types of straight continuity plate formation (arrangement 1-2,1-3and 1-4) show better seismic behavior in deeper beam. Especially continuity plate with haunch system (configuration Type 1-3and 1-4) increases total moment in both beams.
3. When strong column-weak beam of analytical models are greater than 1(type 5-Y), in case of smaller differences of beams' height (beam 50 and beam 40), connection detailing arrangement 3 and 4 (Type X-3 and Type X-4) behave stronger than others. Configuration 3 of connection detailing, Type X-3, is the most efficient connection.
4. Generally connection detailing configuration 2, i.e. Type

x-2, in all types of analytical models, does not show acceptable cyclic behavior and it seems that it could be a result of discontinuity of loading path adjacent to deep beam bottom flange; moreover; the level of absorbed energy is the smallest one.

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