APPLICATION OF LOCAL-DEFORMATION BASED DESIGN METHOD TO VARIOUS STEEL FRAMES

T. Takeda(1), M. Sato(2), O. Lavan(3), M. Kurata(4)

(1) *Graduate student, Faculty of Engineering, Kyoto University, takeda.tadahisa.26x@st.kyoto-u.ac.jp*
(2) *Consultant, Roland Berger, miho.sato@rolandberger.com*
(3) *Associate Professor, Technion, lavan@cv.technion.ac.il*
(4) *Associate Professor, Disaster Prevention Research Institute, Kyoto University, kurata.masahiro.5c@kyoto-u.ac.jp,*

Abstract

Minimal-Disturbance Arm Damper (MDAD) has been proposed within the seismic retrofitting scheme of minimal-disturbance to building users. The MDAD is a light-weight and handy rehabilitation technique and improves the stiffness and strength of the entire frame moderately. The MDAD's notable contribution is its feature in re-distributing the force and deformation demand within the frame from the most vulnerable parts to the other components with reserved capacities. To effectively utilize this structural feature, a local-deformation based design method for the MDAD has been developed for the seismic rehabilitation of existing steel moment resisting frames (SMRFs). Its novel feature is that, it limits the local deformation at critical parts directly. This is a notable update. Many other design methods consider the stiffness and strength of overall frames as the design targets and sometimes increase the force demands to other existing components drastically. As of now, the efficacy of the developed design method was verified only for a benchmark SMRF with a beam collapse mechanism. This paper aims to expand the application of the design method to other frame configurations as a step toward its practical use.

Keywords: Minimal Disturbance, Local Deformation Based Design, Seismic Rehabilitation, SMRFs

1. Introduction

Minimal-Disturbance Arm Damper (MDAD) [1] has been developed within a design scheme of minimal-disturbance to building users and existing frames. This scheme pursues the seismic performance enhancement with the consideration on improved business continuity during and after retrofit by minimizing obstruction to the visual and physical space of building users and the use of heavy construction equipment. The MDAD is a light-weight and handy rehabilitation technique and improves the stiffness and strength of the entire frame moderately. The MDAD's notable contribution is its feature in re-distributing the force and deformation demand within the frame from the most vulnerable parts to the other components with reserved capacities.

The MDAD was designed to reduce the local deformation demand at the bottom flange of beam ends, which often determines the global deformation capacity of steel moment resisting frames (SMRFs) [2-4]. This is a valuable achievement as compared to many other rehabilitation techniques, which normally take an approach of seismic performance enhancement by increasing the strength and stiffness of the entire frame. Thus, for the effective use of the MDAD, a direct design method to limit the local deformation of existing structures with the aid of displacement-based design concepts is considered in this research.

To maximize the benefit of MDAD, a design method which directly aims to limit local deformation was developed for SMRFs with a intended beam-collapse mechanism. First, the closed-form relationship between the plastic hinge rotation at beam ends and story drift was derived for a substructure of one beam and one column with an explicit plastic hinge at its beam end. Then, this local to global deformation relationship was combined with the displacement-based design concept to estimate the local deformation demand for a given earthquake design spectrum. Nonlinear pushover analysis and time history analysis were conducted for a benchmark four-story frame to verify the developed design method in limitting plastic rotations of beam ends to a target value. However, as of now, the design method was verified only in the benchmark frame with a secured beam-collapse mechanism. Thus, the study was expanded to cover other frame configurations as a step toward its practical use.

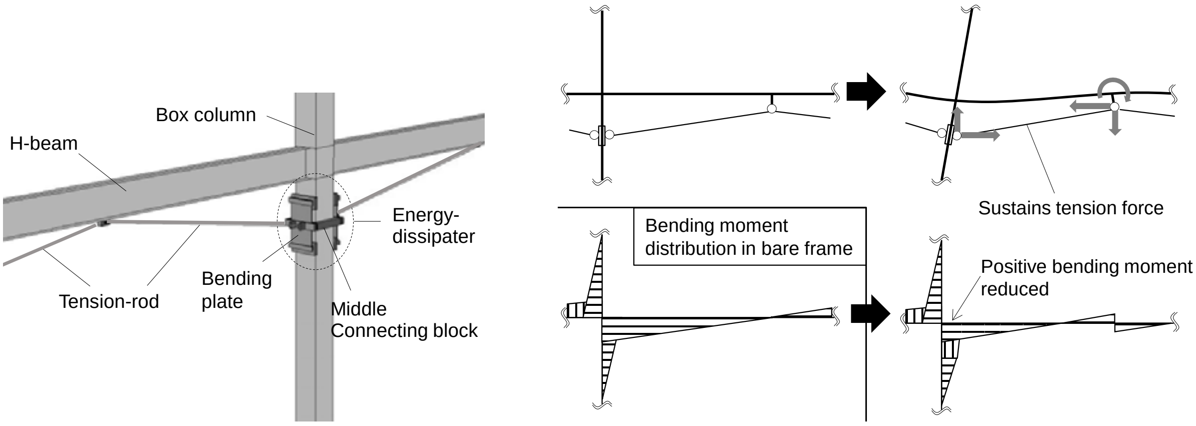
This paper presents the application of the developed design method to SMRFs with distinct seismic performances. More specifically, the design method are applied to three exisitng frames with: (1) column-to-beam strength ratio; (2) column-to-beam stiffness ratio; and (3) span length ratio. In each case, the efficacy and accuracy of the developed design method is verified through a series of nonlinear pushover analyses.

2. Introduction of MDAD

2.1 Schematic and key features

Figure 1(a) shows the schematic of the MDAD that consists of two bending plates and tension-rods. Two bending plates are attached to a hollow structural section (HSS) column at approximately upper one quarter of the story height, and the tension-rods connect the bending plates and the mid-span of beams. The both ends of the tension-rods are pin-supported. The bending plate assembly, called an energy dissipater, is attached to the column by friction using the post-tension rods. The further details of the MDAD can be found in reference [1]. The advantages of such configuration are as follows: (1) the maximum force applied to other structural components are capped by the yielding of the bending plates; (2) the two bending plates connected each other at the middle height deforms out-of-plane simultaneously under cyclic tensile loads and dissipate energy with a stable bi-linear hysteresis; (3) the bending plates can be replaced easily after earthquake events.

Besides the stable energy-dissipation capacity, the MDAD reduces the local deformation at the bottom flange of beam ends under positive bending, called positive plastic hinge rotation hereinafter. Figure 1(b) shows schematically the mechanism to reduce the bending moment and the plastic rotation in beam ends under positive bending. When the tension-rod sustains force, vertical force is applied to the mid-span of the beam. The negative bending moment generated by the vertical force reduces the positive bending moment at the beam end. The yielding of the beam end is delayed and the positive plastic hinge rotation at the beam ends, as the direct damage indicator for the frame, is reduced significantly. The additional bending moment and shear force at the mid-span of the beam are negligible compared to the beam capacity.



(a) (b)

Fig. 1 –MDAD [1]: (a) overall configuration; (b) mechanism to reduce local deformation

2.2 Reduction of local deformation demands in SMRFs

The effectiveness of the MDAD in rehabilitating existing SMRFs was examined through a nonlinear pushover and time history analyses. A four-story frame originally designed with the Japanese building code was selected as a benchmark (Fig. 2(a)). The span and the story height of the frame were 6,000 mm and 3,000 mm, respectively. Fig. 2(b) shows a MDAD analysis model. The bending plates were modelled as zero length spring elements with a nonlinear material behavior. The tension rods are modeled by using tension-only elements and pin connected to the beams and the zero length spring. The deformation capacity of the frame was assessed with the first initiation of beam-end fracture. The fracture of beam-ends was defined as a plastic hinge rotation of 0.015 rad and 0.022 rad in positive and negative bending, respectively, based on literature reviews. The details of the benchmark frame and modeling are described in reference [1].

Based on the pushover analysis results of the bare frame, the first and second stories were rehabilitated with the MDAD. The deformation capacity of the overall frame was enhanced by 23% while the stiffness and strength were increased moderately by 23% and 36%, respectively (Fig. 2(c)). Next, dynamic behaviors were examined with the time history analyses using the ground motions selected in SAC steel project [5]. The results shown in Table 1 demonstrated that the eighty-fourth percentile of the maximum positive plastic hinge rotation was reduced by 43% while the roof drift decreased moderately by 10%.

From these results, the contribution of the MDAD to the reduction of the local deformation can be explained by the combination of the following two effects: (1) the reduction of positive plastic hinge rotation under a certain inter-story drift; (2) mitigated deformation concentration to certain stories, and (3) reduction in the roof drift with the moderate increase in stiffness and strength of the entire frame. These results suggested a need for a new design method that aims to restrain local deformations directly at beam-ends as the SMRFs' critical locations.

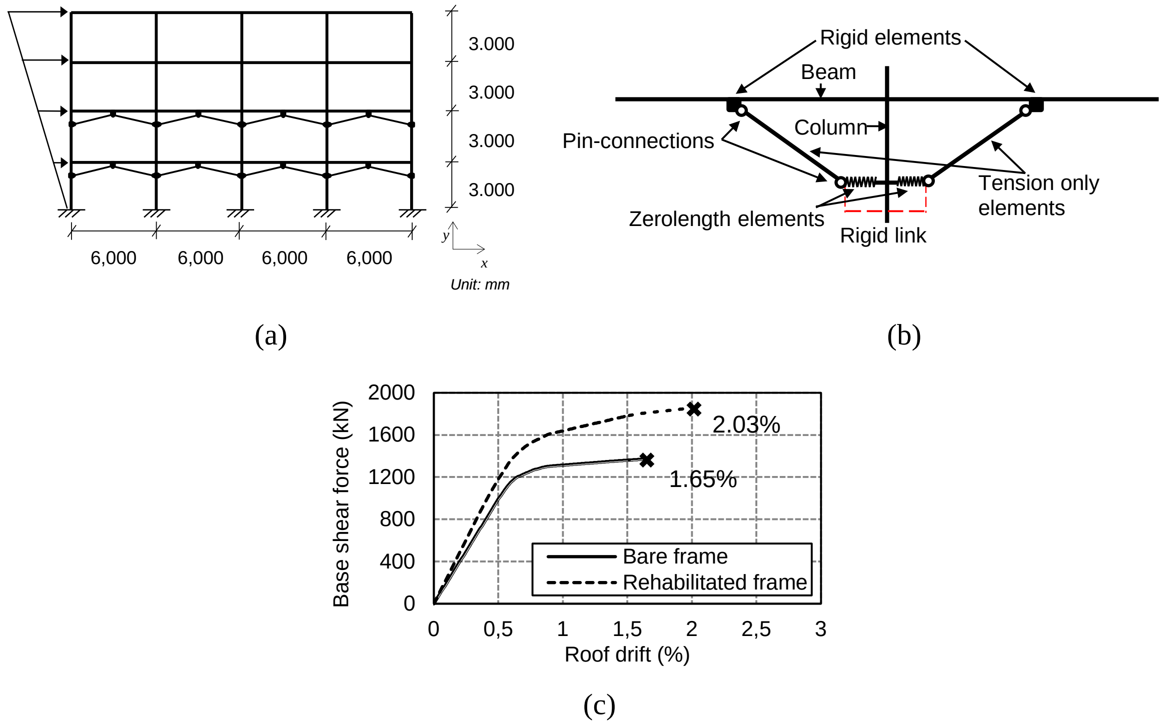


Fig. 2 – Retrofit of four-story SMRF [1]: (a) frame dimensions; (b) MDAD model, (c) pushover results

Table 1 – Eighty-fourth percentile response quantities under LA10-50 motions

	Peak roof drift [%]	Peak 1st story drift [%]	Peak hinge positive plastic rot [rad]	Peak hinge negative plastic rot [rad]
Bare frame	1.99	2.53	0.021	-0.022
Rehabilitated	1.84	2.20	0.012	-0.020

3. Local deformation-based design method

3.1 Overall flow of design

Figure 3 shows the overall flow of the local-deformation based design method. First, inter-story drifts are evaluated by nonlinear time-history analyses. Second, given the global deformation (inter-story drift), the local deformation (plastic hinge rotation) is estimated utilizing a global-local design equation that correlates the two quantities. In detail, a closed-form relationship between the inter-story drift demand, the MDAD strength, and the target plastic hinge rotation is derived using the design substructure which represents the behavior of the frame after beam yielding [6]. Third, the inter-story drifts are assessed again by time-history analyses, in the same way to the first step, to examine the changes in the inter-story drift distribution and roof drifts. If there is any drastic changes, the MDADs are to be designed again by the design equations with updated inter-story drifts. Fourth, now that the desired strength and stiffness of the MDAD is determined, the detailed dimensions such as the bending plate length and tension-rod diameter are computed with design equations. Finally, damages of all the structural members are checked to confirm that the rehabilitation by the MDAD does not cause any undesired collapse mechanism.

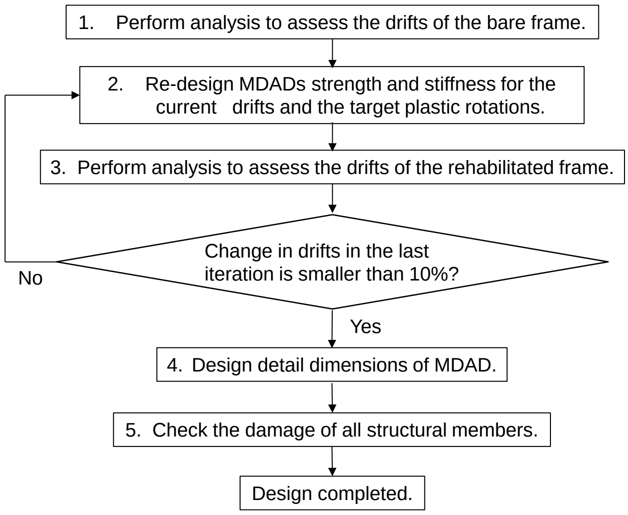


Fig. 3 – Flow of local deformation-based design

3.2 Verification of design method with benchmark four-story frame

The effectiveness of the developed design method was evaluated through a set of nonlinear pushover analyses. The steel frame in Section 2.2 was used again. A N2 method was utilized to estimate the maximum deformation that the frame experiences under earthquake events [7]. For the design spectrum in N2 method, the one defined in the Japanese building code was selected [8]. The selected spectrum was for the second-level design with the maximum acceleration response in the short periods of 1.23 g. The design limit for the positive plastic hinge rotation of beam ends was set to 0.015 rad referring the past experiments [2-4].

The changes in the story drifts and the maximum positive plastic hinge rotation at beam ends over design trials (called cases) are shown in Fig. 4(a) and (b), respectively. Firstly, as “Design case 0”, the pushover analysis and N2 method were applied to the bare frame. Next, the MDADs were designed for each story utilizing the design equations that correlates approximately the local deformations (plastic hinge rotation) and global deformation (story drifts). After completing the design procedures, the pushover analysis and N2 method were conducted again. These results are shown as “Design case 1”. In this case, the story drift distribution changed drastically by the rehabilitation. The maximum positive plastic hinge rotation at the 1st and 2nd story beams fell below the target and that at the 3rd story beams exceeded the target. In such case, the MDAD design are repeated to minimize the error induced by the changes of story drifts and roof drift with the attachment of the MDADs. This check-and-design circulation was repeated until the changes in story drifts became smaller than 10% from the previous design case. In this example, the design converged in three iterations.

The positive plastic hinge rotations at beam ends were found to be properly limited to the target value and the deformation capacity of the entire frame was effectively enhanced. The design procedure successfully led to an efficient design, where the MDADs with a near minimal strength are assigned only to the stories that would reach the limit positive plastic rotation. This achievement is believed to result in the minimal disturbance in retrofit construction and the minimum base shear increases that eliminates the need for foundation and columns strengthening.

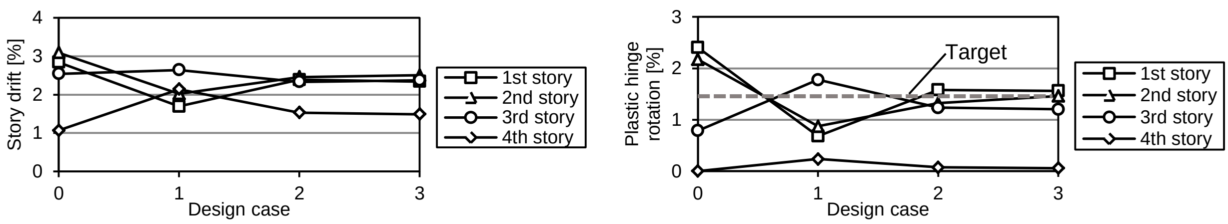


Fig. 4 – Verification of design; (a) changes in story drifts; (b) changes in positive plastic hinge rotation

4. Application of design method for various frames

The efficacy of the proposed design method was verified for a benchmark frame with an intended beam collapse mechanism. As the design method contains several assumptions which possibly decline the accuracy of design under a certain structural feature, the applicable range of the design method is investigated. The accounted structural features in the applications are: (1) column-to-beam strength ratio; (2) column-to-beam stiffness ratio; and (3) span length ratio. In every case, the accuracy and validity of the design method were verified by a set of frame analyses.

4.1 Column-to-beam strength ratio

The influence of the column-to-beam strength ratio (the CBSR) on the accuracy of design method was evaluated by a series of nonlinear pushover analyses. The CBSR defined as the column plastic strength over the beam plastic strength were decreased gradually from 1.8 to 1.2. The CBSR of 1.8 guaranteed a beam collapse mechanism. The CBSR was adjusted simply by changing the yielding stress of the column section. This aimed to keep the column-to-beam stiffness ratio unchanged and purely examine the influence of the CBSR. The design method was applied to each building model with the different CBSRs. As with the design case shown in Section 3.2, the MDAD was designed with the positive plastic hinge rotation at beam ends of 0.015 rad.

Figure 5 shows the results. For all cases, the positive plastic hinge rotation at the beam ends became approximately to the target rotation (Fig. 5(a)). For the cases with the CBSR of 1.4 or smaller, the story drift of the 3rd story increased drastically with the formation of a soft-story (Fig. 5(b)). Essentially even in case of a soft story formation, the MDAD should be designed appropriately to limit the positive plastic hinge rotation. However, they were not, due to the definition of the story drift based on the assumption of a beam-collapse mechanism. This attribute to the definition of the “story drift” in the design method, which is defined as the average of adjunct two inter-story drifts. For instance, the average of the 3rd and 4th inter-story drifts is referred in the design equation to design the MDAD in the 3rd story. This approximation is valid as long as column deformations are limited (Fig. 5(d)). When the soft story is formed, as the cases of with the CBSR of 1.4 or smaller, the average story drift became smaller than the story drift in the 3rd story (Fig. 5(e)). As a result, the design method failed to judge the necessity of retrofit in the 3rd story. To summarize these analyses, it can be concluded that the developed design method is not appropriate to the building which has too weak column with the CBSR below 1.4. For such buildings, the improvement of the design method will be desired.

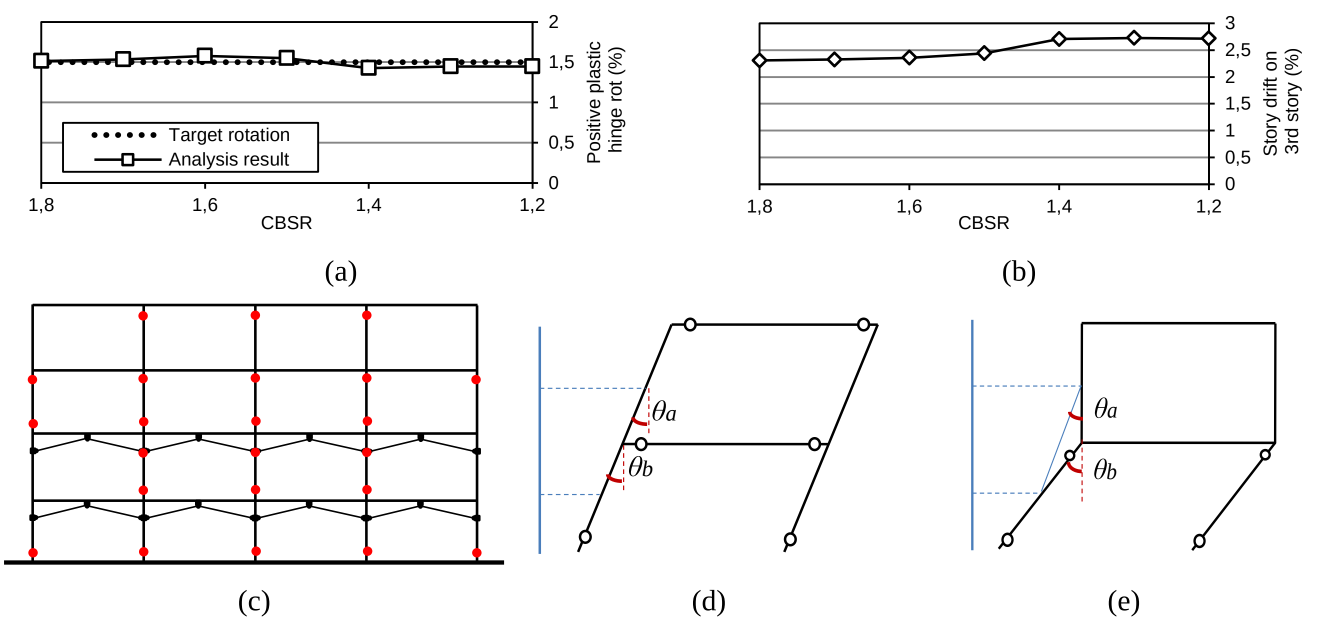


Fig. 5 – Influence of column-to-beam strength ratio: (a) beam plastic hinge rotation; (b) story drift in 3rd story; (c) location of plastic hinge; (d) story drift distribution in beam collapse mechanism; (e) story drift distribution in soft story mechanism.

4.2 Column-to-beam stiffness ratio

Next, column-to-beam stiffness ratio, R_k, defined as the column bending stiffness over the beam bending stiffness is considered as a structural feature. The benchmark frame introduced in Section 2.2 had the R_k of 2.5. In this section, the MDAD was designed for frames with R_k from 1.0 to 4.0. For the sake of simplicity, as well as the study in Section 4.1, R_k was adjusted by changing the elastic modulus of the columns, while the dimension of the beams and columns was kept unchanged through all cases.

Figure 6 shows the result of pushover analysis in terms of the positive plastic hinge rotation at the beam ends. In almost all cases, the plastic hinge rotation were limited successfully within the target rotation. For the case of R_k = 1.0, the discrepancy between the pushover result and the target rotation exceeded 5%. When the initial stiffness of the MDAD was computed in the design method, the elongation of the tension rods in the MDAD was calculated with the assumption that the elastic deformation of the column be negligible. However, this is not true for small R_k. Nonetheless, the discrepancy is sufficiently small about 5% even for extraordinary flexible columns and thus the design method is believed to be valid regardless of R_k.

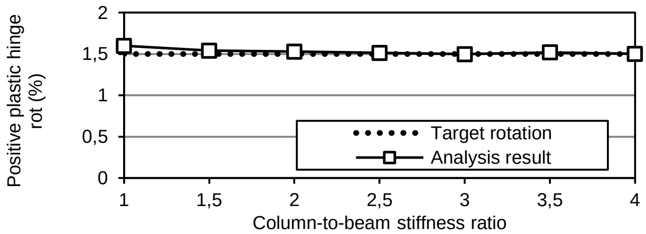


Fig. 6 – Column-to-beam stiffness ratio

4.3 Long and short span length

The performance of the design method in case of frames with uneven span were considered. Fig. 7 shows a frame with longer exterior spans and shorter interior spans. The dimension of the beams and columns were consistent to the baseline frame in Section 2.2 except the span lengths. Considering simplicity in design and construction, all the MDADs at the same story are assumed to have the same dimensions. As the beam ends in the shorter span sustains larger plastic hinge rotations compared to those in the longer span, the MDAD dimensions were designed for the demands computed for the shorter spans. This naturally led a conservative design.

The design method successfully limited the positive plastic hinge rotation at beam ends without any updates in the design methodology. The design was completed after three iterations. Table 2 shows the variations of positive plastic hinge rotations within the same story. There observed a nicely-controlled positive plastic hinge rotation at the shorter span. With an aim to prevent the fracture at beam ends, the demonstrated that the effective design was achieved without suggesting the needs on updating the current design method.

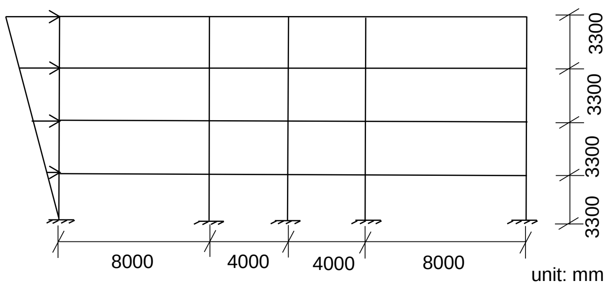


Fig. 7– Geometry of the frame with long and short spans

Table 2 – Variations of plastic hinge rotation between within the same story

	Left span	Mid-left	Mid-right	Right
Span length	Long	Short	Short	Long
Positive plastic hinge rotation at beam end [%]	1.21	1.50	1.50	1.07

5. Conclusions

With the aim to expand the application of the local deformation-based design method of MDAD to SMRFs with various structural features, numerical studies focusing on three parameters, 1) column-to-beam strength ratio, 2) column-to-beam stiffness ratio, and 2) span length distribution, were conducted. The accuracy and efficacy of the developed design method were examined in each case study.

The study for the column-to-beam strength ratio revealed that the design method tends to fail in successful design of MDADs for the SMRFs with weak columns where a soft story collapse are likely formed. This was caused by the discrepancy in evaluating average story drifts that is essential to compute the strength and stiffness of MDAD using the derived close-formed relationship of target positive plastic hinge rotation, story drift demand, and MDAD strength. Therefore, the current design method does not work well for weak-column structures under the ratio of 1.4.

For the study for the column-to-beam stiffness ratio revealed that even though the column is extremely flexible or rigid, the design method works precisely without any significant errors. Also, for the frames with uneven span lengths, the design method succeeded to limit the positive plastic hinge rotation at beam ends in the shortest span, as most critical parts with largest deformation demand, without any modifications on the design method.

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