AN INNOVATIVE SEISMIC DESIGN FOR REPAIRABLE REGULAR STEEL BUILDINGS BY USING ROCKING MOTION AND CIRCUMFERENTIAL ENERGY DISSIPATING COLUMNS AT BASE LEVEL

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ABSTRACT

Most of seismic design codes accept heavy structural damages in case of large earthquakes, provided that the building is prevented against collapse. However, this has unacceptable consequences, such as very heavy required reconstruction works in large populated cities. One approach for preventing theseconsequences is the idea of 'Deliberate Directing of Damage', which means guiding the damage to some pre-decided parts of the structural system so that other parts do not experience any plastic deformation. Here thisidea was employed for design of regular steel multi-story buildings, to be repairable after a large earthquake, by activating the rocking motion of the building using a specific giant central column, and energy absorbing circumferential columns at the lowest story. The giant central column not onlycarries most of the gravity loads, but also causes the building structure to have rocking motion under the seismic loadings. The energy dissipating columns are equipped with Double-ADAS (DADAS) devices, which can be easily replaced if necessary. To assess the efficiency of the proposed system a set of multi-story buildings with square plan were designed, once based on the conventional provisions, and once by using the suggested system, and thena series of nonlinear time history analysis were conducted on them using several 3-component accelerograms of selected earthquakes. Results show that the suggested system leads to a more reliable seismic behavior of the building so that plastic deformations happen basically inDADAS devices, and just a few hinges at the Immediate Occupancy performance level may appear in other parts of the building structure. Furthermore, the rocking buildinghas longer period, comparing to the ordinary building, resulting in lower acceleration values in the building, leading to reduction of the seismic forces imposed to the building, and giving higher safety level to nonstructural elements.

Keywords: Seismic Codes, DDD Technique, Nonlinear Time History Analysis, DADAS Devices.

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1. INTRODUCTION

The philosophy behind most of seismic design codes implicitly accepts heavy damages of the building in case of large earthquakes, provided that the building is prevented against collapse. However, this philosophy, in case of large populated cities located in the vicinity of active faults, leads to unacceptable consequences, such as large number of people who lose their living or working places for a long time, very difficult demolishing work of the heavily damaged buildings, and very large volume of the required reconstruction works.

To avoid these adverse consequences one approach is design of 'repairable structures' for buildings, by using the idea of 'Deliberate Directing of Damage' (DDD), introduced by the first author (Hosseini and Alyasin 1996), which means guiding the damage to some pre-decided parts or elements of the structural system, so that other parts do not experience any plastic deformation, and therefore, the structure can be easily repaired. Although this technique has been introduced basically for pipelines, it can lead to a new generation of earthquake-resisting buildings, and researchers have introduced and worked on similar ideas for building systems, among them using the energy dissipating devices or structural fuses can be mentioned, which have been introduced in late 70s to early 80s (Fintel and Ghosh 1981), and have been developed more in recent years (Vargas and Bruneau 2006). It should be noted that in these studies, although the main idea is concentration of damage in energy dissipators or fuses, and keeping the main structural members elastic or with minor easily repairable damages, in reality the building can not remain in Immediate Occupancy (IO) Performance Level (PL), and needs to be evacuated, at least partially, for repair works.

To overcome this shortcoming, the use of rocking motion of the building has been proposed by some researchers in recent decade (Midorikawa et al. 2002). They used weak base plates, attached to the bottom of each steel column at the first story, to cause rocking vibration under appropriate control, and conducted more recently an experimental study on a structural frame with rocking motion (Azuhata et al. 2008). Although their proposed rocking structural system is quite effective is seismic response reduction, their studies is limited to 2-dimensional systems. In recent years, the first author of this paper has used the idea of rocking motion of building in combination with a central fuse, which works as a huge plastic hinge under the vertical load and the moment, induced by the lateral seismic load (Hosseini and NoroozinegadFarsangi 2011, Hosseini and Kherad 2013).

In this study, the DDD idea has been employed for design of regular steel multi-story buildings, to be repairable after a large earthquake, by activating the potential of rocking motion of the building using a giant central column with specific features, making the building to move in rocking motion, and energy absorbing circumferential columns at the lowest story of the building. The detail of the study is presented in the following sections.

2. INTRODUCING THE PROPOSED ENERGY-DISSIPATING ROCKING STRUCTURAL SYSTEM FOR MULTISTORY BUILDINGS

In the proposed structural system for regular multi-story steel buildings the columns of the lower story have been replaced by a central specific giant column and a series of circumferential columns with energy dissipation capability. The giant central column plays two important roles in the proposed system:1) it carries most of the gravity loads of the building all the time, and 2) it makes the building structure to go in the rocking mode under the seismic loadings. Each of the circumferential energy dissipating columns has a Double-ADAS (DADAS) energy dissipating device (Hosseini and Bozorgzadeh 2013), which gives the remarkable energy dissipation capability to the columns subjected to extensive axial loads. The DADAS devices can be easily replaced with new ones after a large earthquake. To compensate the elimination of other interior columns of the lowest story, instead of ordinary beams, strong girders are considered in that story to transfer the loads of the interior columns of all upper stories to the central and circumferential columns at the lowest story, as shown in Figure 1.

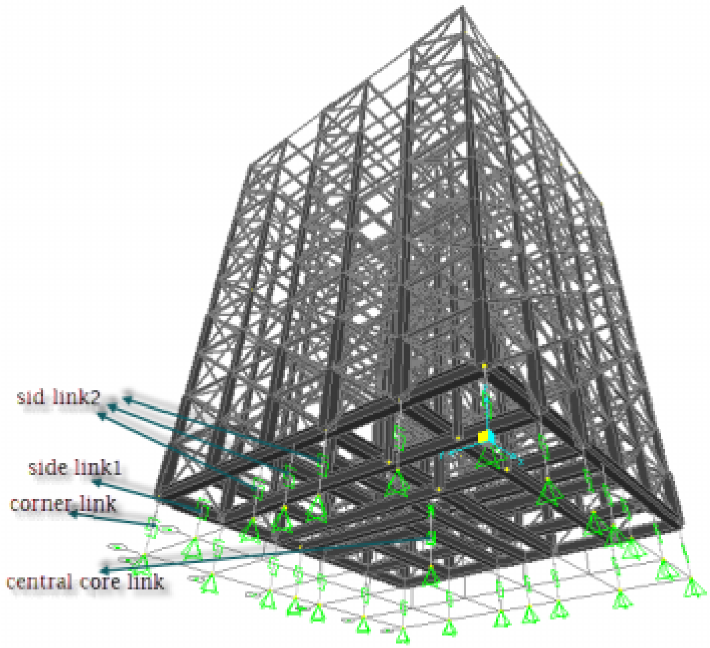

Figure 1: A view of the proposed rocking energy-dissipating structural system

Inthis study, the main core column is designed to remain elastic all time, and all energy dissipation take place in the DADAS devices, provided in the circumferential columns at the lowest story. Figure 2 shows schematically a sample of the DADAS devices with its hysteretic force-displacement curves.

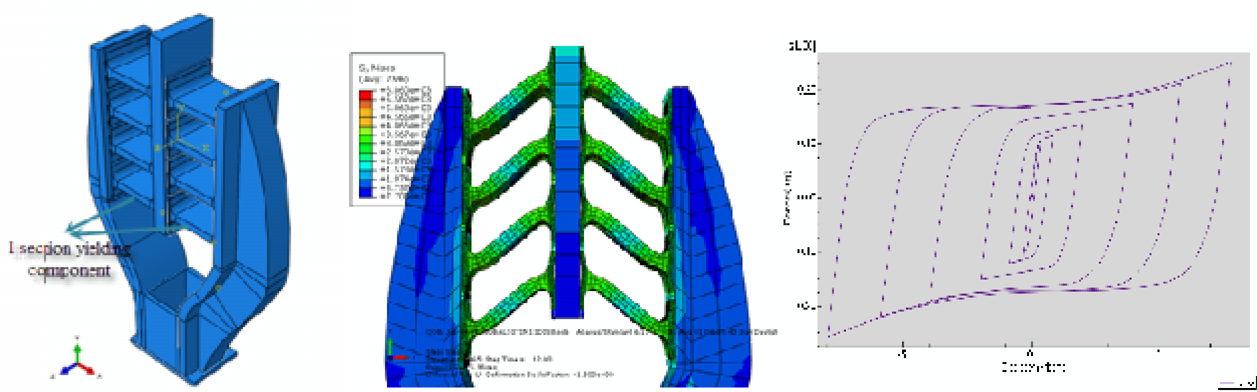

Figure 2: Schematic views of the proposed DADAS device, and its hysteretic curves

To assess the realistic hysteretic force-displacement curve of the proposed DADAS device, a powerful finite element (FE) program was used, and to verify the numerical modeling the results of an experimental study on the yielding bracing system (YBS) were used (Gray et al. 2010). Figure 3 shows the YBS prototype under test along with the its numerical FE model, developed by the authors, as well as the hysteretic curves obtained by, respectively, experiment and numerical model.

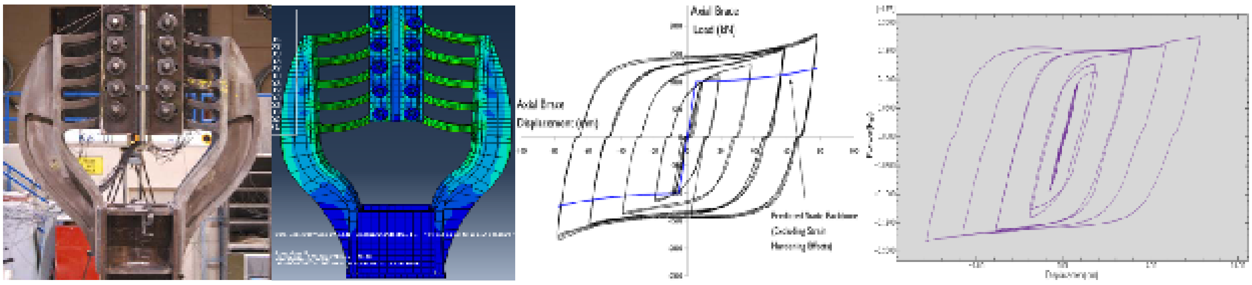

Figure 3: The YBS, its FE model, and its experimental and numerical hysteretic curves

The satisfactory precision of the FE numerical molding can be seen in the hysteretic curves shown in Figure 3. It should be noted that in the proposed DADAS device some I-section elements are used instead of the finger-type elements used in the YBS. The advantage of using I-section elements, in comparison to the finger-type elements, is creation of more potential for plastic deformation, and therefore, more energy dissipation capacity, for a given axial deformation in the device. In fact, in the finger-type element there is just one location for plastic deformation, while in the I-section element, there are six locations, as shown in Figure 4, which shows one of the I-section elements and its hysteretic behavior.

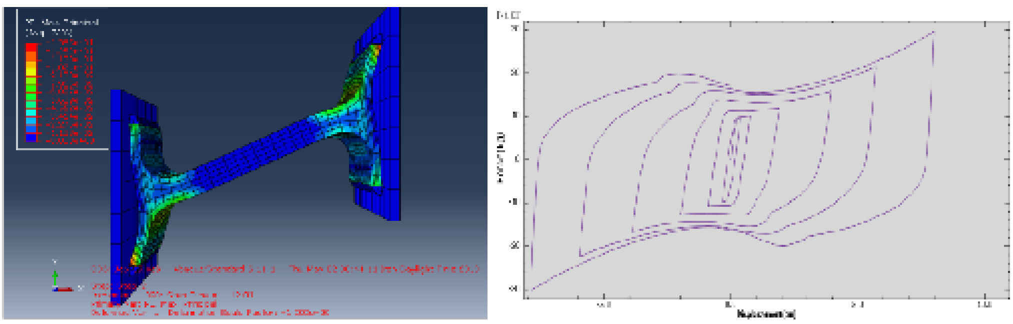

Figure 4: Plastic deformation of the I-section element of the DADAS device under axial deformation imposed to the device, and its numerically obtained hysteretic curves

It is obvious that the stiffness and strength of the proposed DADAS device are respectively equal to those of the I-section element times the number of I-section elements used in the device. On the other hand, the stiffness and strength of each I-section element depend on its geometrical and mechanical features. In this way, by choosing the appropriate dimensions of this element and an appropriate number of them in the DADAS device the desired stiffness and strength can be obtained for the DADAS device. In this study different values were used of the dimensions of the I-section element to see how they affect the hysteretic behavior of the DADAS device. The sample curves shown in Figure 4 relate to an I-section element with height of 25.0 cm, width of 20.0 cm, flange length of 14.0 cm and web and flange thicknesses of 2.5 and 1.0 cm, respectively. More results of the type shown in Figure 4, obtained by using other values for these dimensions can be found in the main report of the study (MousaviTirabadi2013).

3. CONSIDERED BUILDINGS AND THEIR SEISMIC RESPONSE

The buildings considered in this study for showing the efficiency of the proposed structural system in seismic response reduction, include a 7-, a 10-, and a 14-storyregular steel building, all with 5-bay×5-baysquare plan, in which span length of all bays is 4.0 m and height of all stories is 3.0 m. The building was designed once based on the conventional provisions (Iranian Standard No. 2800, which is very similar to the UBC), and once by using the suggested system. The yielding force of the DADAS devices used in the three buildings are given in Table 1.

Table1: Yielding force of the DADAS device of corner, side, and middle columns of the buildings

No. of stories	Yielding Force (kgf)		
	Corner	Side	Middle
7	41500	62500	62500
10	62500	62500	93000
14	66000	88000	110000

The percentage of gravity loads carried by the corner, side, and middle columns depend on their relative stiffness, and are as shown in Table 2.

Table 2: The percentage of gravity loads carried by the circumferential columns

No. of stories	Corner	Side	Middle	All circumferential columns
7	6.00	17.86	17.86	41.72
10	6.25	12.50	27.90	46.65
14	5.10	13.50	25.10	43.70

As it can be seen in Table 2, the total percentage of the gravity loads, carried by all circumferential columns in three different buildings is less than 50, which mean that more that 50% of these loads is carried in all cases by the central core columns.

Table3: Inputaccelerogramsused for NLTHA

Record Name	PGA(g)	Total Duration (sec)	Effective Duration (sec)
Tabas 1	0.856	32.82	32.82
Tabas 2	0.917	32.82	32.82
Tabas 3	0.733	32.82	32.82
Chi-Chi Taiwan 1	0.894	89.99	24.00
Chi-Chi Taiwan 2	1.092	89.99	24.00
Chi-Chi Taiwan 3	0.72	89.99	24.00
Loma Prieta 1	0.519	39.95	18.00
Loma Prieta 2	0.433	39.95	18.00
Loma Prieta 3	0.543	39.95	18.00

The considered buildings were analyzed by nonlinear time history analysis (NLTHA) using several 3-component accelerograms of selected earthquakes, covering a specific range of frequency content and PGA values, compatible with the assumed site conditions. To model the circumferential columns, equipped with DADAS devices, the bilinear link, available in the common structural analysis programs, were used. Three types of these bilinear links were required, respectively for corner, side, and middle columns, whose numbers are respectively one, two, and three in each side of the building (see Figure 1). The 3-component records used for NLTHA are introduced in Table 3.The outputs considered for comparing the seismic behavior of the two sets of buildings include the number of plastic hinges in various PLs, roof displacement and acceleration time histories, and driftsof the buildings at their different stories. Figure 5 shows the number of plastic hinges formed in various PLs in case of the 10-story buildings as a sample.

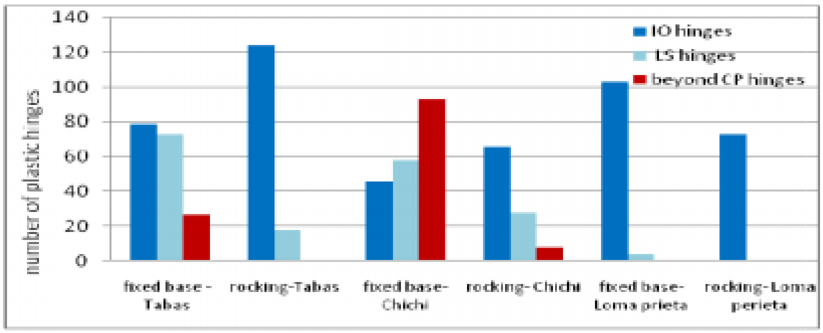

Figure 5: Number of plastic hinges at various PLs formed in fixed-base and rocking buildings subjected to three used earthquakes

Figure 5 shows that in fixed-base buildings in cases of Tabas and Chi-Chi earthquakes some hinges beyond the CP PL, and in case of Loma Prieta earthquake some LS hinges have been created, while in rocking buildings in case of Tabas earthquake only some LS hinges, and in case of Loma Prieta earthquake only IO hinges have been created, and only in case of Chi-Chi earthquake a few CP hinges have been created. This means that the rocking system remarkably improve the seismic behavior of the buildings.As other samples of the results, figure 6 shows the plastic hinges formed in the two corresponding frames of the 10-story buildings subjected to Chi-Chi earthquake.

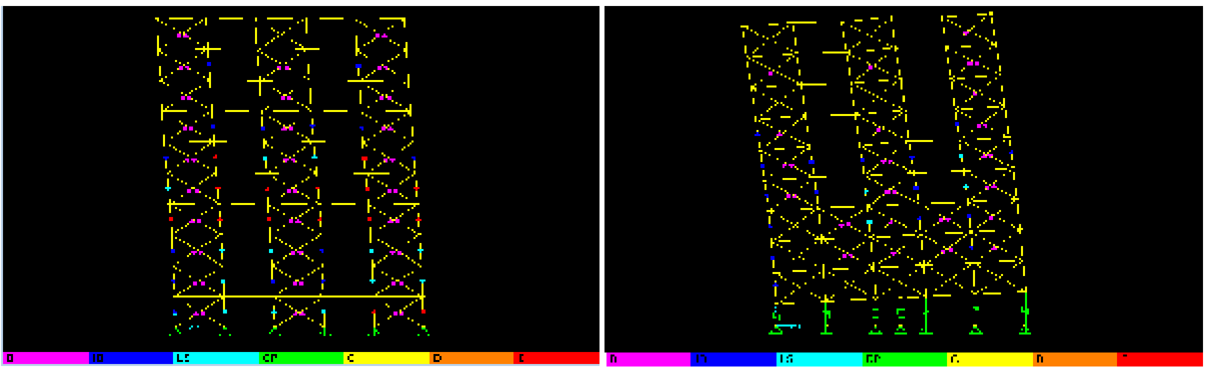

Figure 6: Plastic hinges in various PLs formed in two frames of the 10-story buildings with conventional design (left) and proposed design (right) subjected to Chi-Chi earthquake

Figures 7 and 8 show, respectively, the roof displacement and the roof acceleration time histories of the 10-story buildings subjected to Tabas earthquake in x and y directions.

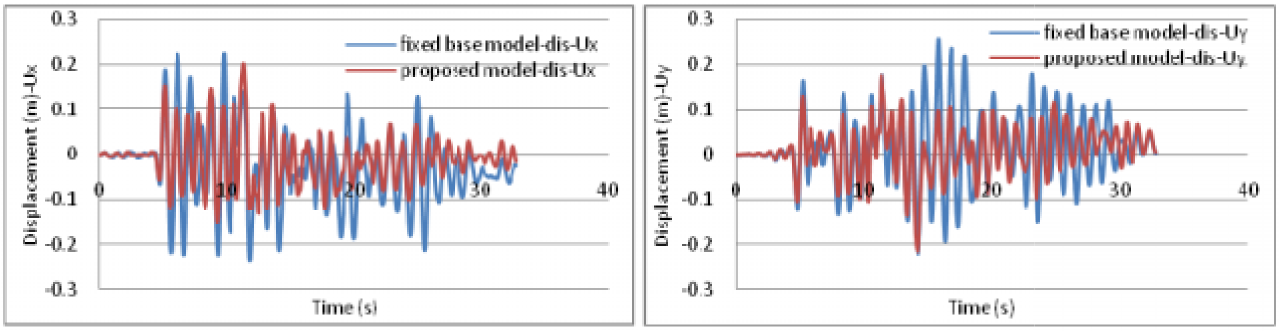

Figure 7: Roofdisplacementtime historiesof the 10-story buildings subjected to Tabas earthquake in x and y directions

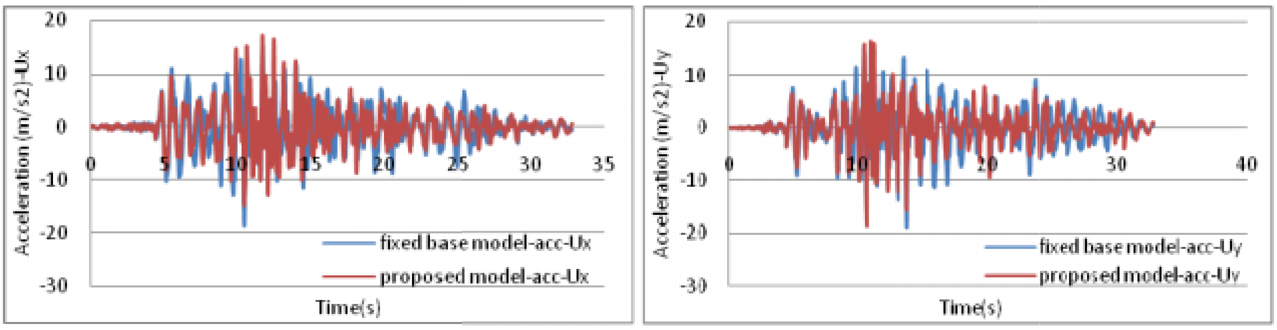

Figure8: Roof acceleration time histories of the 10-story buildings subjected to Tabas earthquake in x and y directions

It is seen in Figures 7 and 8 that both displacement and acceleration responses of the rocking buildings are lower than those of the corresponding ordinary buildings. As the last sample of the results, the maximum drift values of the 10-story buildings subjected to Tabas earthquake, in x and y directions, are shown in Figure 9.

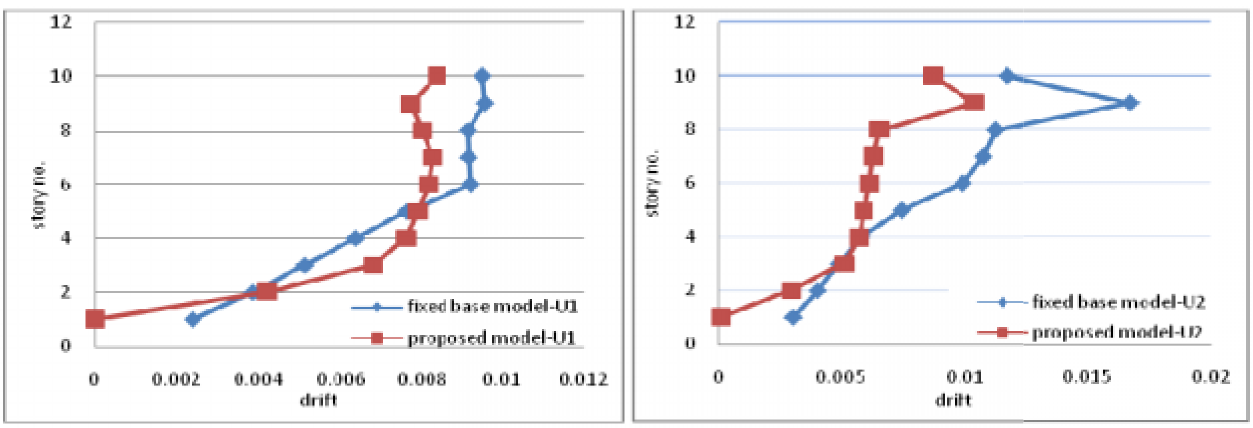

Figure 9: Maximum drift values of the 10-story buildings subjected to Tabas earthquake in x and y directions

It is seen in Figure 9 that the drift values of the rocking buildings are generally lower than their corresponding ordinary buildings, and just in some lower stories the situation may be inverse, however, even in such cases the drift values are lower than the code limits.

4. CONCLUSIONS

Based on the numerical results it can be concluded that:

- The suggested structural system leads to a more reliable seismic behavior of buildings.
- Plastic deformations happen mainly in the DADAS devices at ground floor, and in most casesonly a few hinges at the IO performance level appear in other parts of the building structure.
- The rocking motion leads to longer period values and, therefore, lower acceleration values in the building stories which not only results in reduction of the seismic forces imposed to the building system, but also helps higher safety level of nonstructural elements in the whole building.

Considering the advantages of the proposed rocking and energy-dissipating structural system for buildings the use of this system can be strongly recommended for buildings in the vicinity of active faults, particularly in large populated cities.

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