An earthquake-resistant building system to reduce floor accelerations

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ABSTRACT: This paper presents the results of a research program on an earthquake-resistant building structural system in which the lateral force resisting system (LFRS) is connected to the gravity load resisting system (GLRS) using a deformable connection instead of a rigid connection. The GLRS and LFRS are able to move relative to each other, and depending on the characteristics of the connection it is possible to limit the floor accelerations and the overall response of the structure. Time history numerical analysis is used to determine the response of the structure. The development and testing of a full-scale deformable connection, which is accessible for inspection and replacement, is presented herein. The deformable connection consists of a buckling restrained brace (BRB) or a friction device (FD) which acts as a limited-strength load-carrying hysteretic component, in parallel with low damping rubber bearings (RB) which provide the required out-of plane stability to the LFRS, post-elastic in-plane stiffness, and help with partial re-centering. The nonlinear response of the deformable connection has been demonstrated by full-scale components tests at the NEES@Lehigh equipment site. The tests have been used to calibrate numerical models of this type of connection for use in nonlinear time history analysis of the structural system.

1 INTRODUCTION

The inertial forces generated in building systems during an earthquake ground motion are directly related to the floor system acceleration and the seismic mass (associated with the floor system). In conventional earthquake-resistant building systems the gravity load resisting system (GLRS), in particular, the floor system, where most of the seismic mass is located, is rigidly attached to the lateral force resisting system (LFRS), which resists the seismic inertial force. The inertial force is transferred from the GLRS to the LFRS assuming a rigid connection between the floor system and the LFRS.

It has been shown that the seismic inertial forces generated in the floor system can be substantially high and can lead to inelastic non-ductile response of a diaphragm (Fleischman and Farrow 2001). The development of excessive inertial force due to high floor accelerations can produce nonlinear response and damage of the LFRS that may lead to unsatisfactory seismic response (Rodriguez, Restrepo and Carr 2002; Rodriguez, Restrepo and Blandon 2007). The nonlinear response of the LFRS can act as a "cut–off" mechanism that may limit the floor acceleration (Kelly 1978; Ray-Chaudhuri and Hutchinson 2011). However, even when ductile nonlinear response of the LFRS occurs high floor accelerations may be observed, due to significant contributions to the response from second and higher modes (Ray-Chaudhuri and Hutchinson 2011; Sewell, Cornell, Toro and McGuire 1986). Studies of LFRS with flexural response controlled by inelastic rotation at the base show that high floor accelerations due to the higher-mode contribution on the response can be expected (Chopra 2007; Roke 2010; Amaris Mesa 2002; Wiebe and Christopoulos 2009; Wiebe L., Christopoulos, Trembley and Leclere 2013).

In 1975 Skinner et al. sketched a building system with a "separated tower and frame" where the tower represents a stiff LFRS and the frame represents a flexible GLRS. The system concept allowed relative deformation between the LFRS and GLRS using a deformable link element. Since the LFRS and GLRS have different dynamic characteristics (the LFRS is stiff with a small mass, the GLRS is flexible with a large mass) this system concept enables energy to be dissipated by the link element when significant relative deformation occurs (Skinner, Kelly and Heine 1975). In 1984 Key performed a parametric numerical study to assess the effect of using an energy dissipation device to link the LFRS with the GLRS and showed that using the link element can reduce effectively the base shear of the GLRS and the LFRS (Key 1984). In 1998 Luco and De Barros studied the ability to control the seismic response of a composite tall building modelled by two shear beams interconnected with stiff or flexible link elements (Luco and De Barros, 1998). In 2000 Mar and Tipping presented schematic structural details for a story isolation system. They compared time history numerical analysis results for a conventional system (with a rigid link between the LFRS and GLRS) and the system with floor connected to the LFRS with viscous dampers and linear springs as link elements. The results showed reduced base shear and roof acceleration (Mar and Tipping 2000). In 2004 Crane conducted shake table tests on two small-scale 6 story buildings that had energy dissipative connections between the floors and the LFRS. Triangular-Plate Added Damping and Stiffness devices were used as the link elements. Reduced floor accelerations and base overturning moment were observed (Crane 2004). Amaris et al. (2008) and Johnston et al. (2014) presented alternative discrete and dissipative connections between the LFRS and floor diaphragm (Amaris, Pampanin, Bull and Carr 2008) (Johnston, Watson, Pampanin and Palermo 2014).

Based on this previous research, it appears that a deformable connection can be developed to allow relative motion between the LFRS and GLRS. In the present research, the objective of using such a deformable connection is to limit the force transferred from the GLRS to the LFRS at each floor level, and to reduce the floor accelerations. The use of the deformable connection makes it possible to mitigate the higher mode seismic response, and to reduce the LFRS story shear forces. The energy dissipation from the nonlinear response of the deformable connection is a potential further benefit of using the deformable connection but it is not the main objective, as in some of the previous studies. The deformable connection needs to be constructable, accessible for inspection, and repairable.

2 CONCEPTUAL DESIGN

To allow relative motion between the LFRS and the GLRS, an opening is needed at each floor around the LFRS (e.g. shear walls), as shown in Figure 1. The close up in Figure 1 demonstrates how the deformable connection can be used to connect the LFRS with the GLRS. The concept studied in this research uses two different types of components in the deformable connection.

The first component is a limited-strength, load-carrying hysteretic component (Fig. 1a), which is required to transfer the inertial force from the floor to the LFRS and to ensure the stability of the GLRS. During an earthquake excitation, the limited-strength load-carrying hysteretic component will deform axially due to the horizontal relative motion in the plane of the LFRS. The characteristics of the limited-strength load-carrying hysteretic components determine the magnitude of force that can be transferred from each floor to the LFRS, which determines the magnitude of the floor accelerations that can develop.

The second component of the deformable connection (Fig. 1b) is needed to provide out-of-plane stability to the LFRS. Such components brace the LFRS against the floor system, which is then braced by an orthogonal LFRS. These components are called "bearings" and they must have significant compressive stiffness and strength to transfer the out-of-plane bracing force without significant deformation. The bearings need to have low shear stiffness compared to their compressive stiffness. Their response under shear deformation due to the horizontal relative motion in the plane of the LFRS provides additional stiffness to the deformable connection.
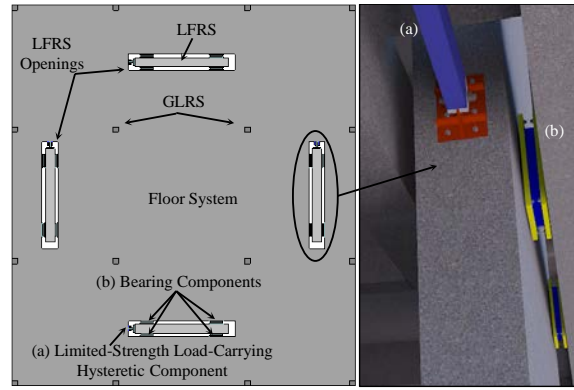
Figure 1. Conceptual design of proposed building system with deformable connections.

3 NUMERICAL ANALYSIS

A numerical analysis was performed to evaluate the deformable connection. The open source software OpenSEES (McKenna, Fenves, Scott and Jeremic 2000) was used to develop the numerical model shown in Figure 2. The building structure is a twelve story special reinforced concrete shear wall structure with plan dimensions 30.48 m x 54.86 m (100 ft. x 180 ft.). It was designed using ASCE7-10 (ASCE 2010) (R = 5, Ωo = 2.5, Cd = 5) assuming that it is located at Berkeley, CA. The Friuli 1976 earthquake ground motion component TMZ000 was used in the analysis. The ground acceleration was scaled by 2.77 to match its spectral acceleration with the design spectral acceleration (ASCE 2010) near the first mode period of the structure. Results from the nonlinear time history analysis in Figure 3 and Figure 4 are used to compare a system with a rigid connection between the LFRS and GLRS, with the system with a deformable connection. The twelfth floor acceleration time histories in Figure 3a demonstrate that the absolute peak floor acceleration is reduced by nearly 50% (from 1.3g to 0.7g) using the deformable connection. In Figure 3b the Fourier amplitude spectra of the twelfth floor acceleration histories demonstrate that the deformable connection significantly reduces the acceleration amplitude near the second (4Hz) and third (11Hz) mode frequencies of the structure. Thus, it is possible to limit these higher mode contributions to the total structural response. The deformable connection used in the analysis has a bi-linear force deformation response shown in Figure 4a. The reduction of the floor acceleration reduces the LFRS twelfth story shear by about 85% (from 14,000kN to 2000kN) as shown in Figure 4b. The LFRS and GLRS twelfth story drift is reduced, as shown in Figure 4c, d, respectively. The reduction of the response is not the same at every floor of the structure. The analytical study shows that the earthquake-resistant building systems with the deformable connection are promising to achieve reduced structural response.
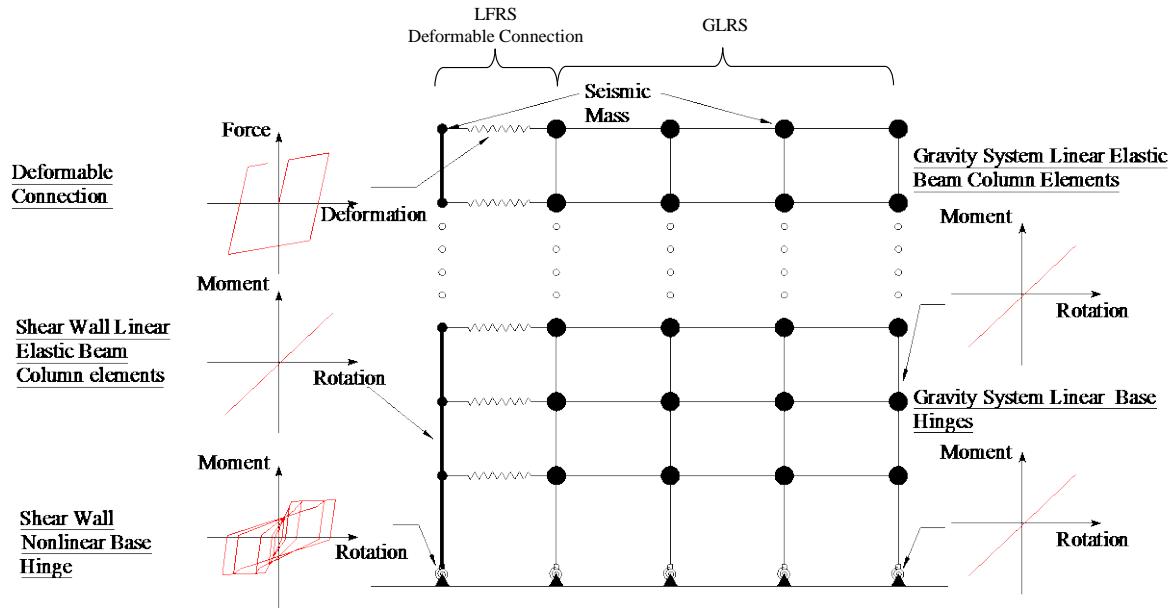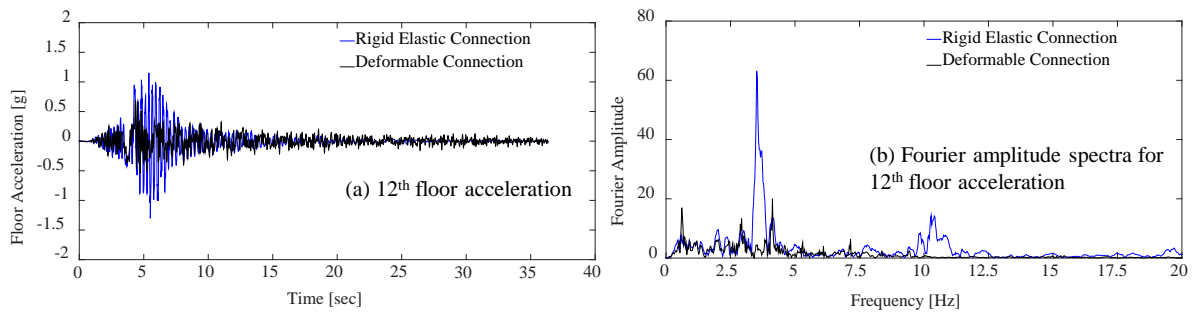
Figure 2. Numerical model.

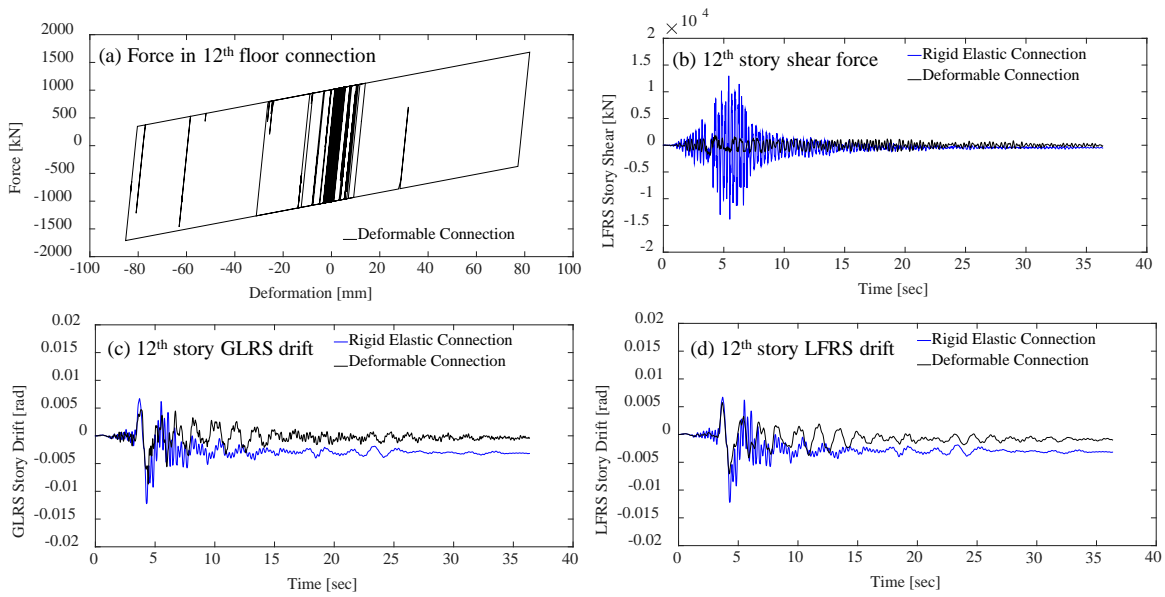**Figure 3. 12th floor acceleration time history and Fourier amplitude spectra.**

Figure 4. 12th floor/story response.

4 IMPLEMENTATION OF THE DEFORMABLE CONNECTION

Extensive research on devices that might be used as components of the deformable connection was carried out and led to two different configurations. The first configuration consists of a buckling restrained brace (BRB) which is used as the limited-strength load-carrying hysteretic component and low damping rubber bearings (RB). BRBs are commonly used in seismic design practice and are commercially available. Individual BRB response has been extensively studied and it has been shown that they provide stable nonlinear hysteretic response. The strength and stiffness of a BRB are closely related but it is possible to design a BRB to have the appropriate nonlinear characteristics for the deformable connection. RB are an appropriate choice for the bearings of the deformable connection. Their compressive stiffness is significantly higher than their shear stiffness. Low damping rubber bearings have large shear deformation capacity, and their response is approximately linear elastic (Huang, Whittaker and Luco 2010).

The second configuration uses a friction device (FD) as the limited-strength load-carrying hysteretic component. RB are also included. For the FD, the strength and stiffness are not as closely related as for the BRB. Thus, a wider range of combinations of strength and stiffness can be considered for the deformable connection. However, FDs are not commonly used in seismic design practice. Thus, a FD that can accommodate the expected kinematics of the deformable connection was developed and validated experimentally. Therefore, one of the objectives of the present research is to study the deformable connection using friction devices.

Figure 5 shows an installed deformable connection on a half-scale rocking shear wall structure built and tested at the NEES@UCSD Large High Performance Outdoor Shake Table (LHPOST) (Fleischman et al. 2015). The objective of this work was to validate the structural response of a building with and without deformable connections between the LFRS and GLRS. Figure 5a shows the elevation of the main rocking wall with deformable connections. The accessibility and minimum architectural impact can be observed. Figure 5b shows a close up view of the FD of the deformable connection. The attachment of the FD to the floor system and the shear wall (Figure 5b) was designed using standard details. RB are shown in Figure 5c. The FD and RB are positioned so they can be inspected after an earthquake.
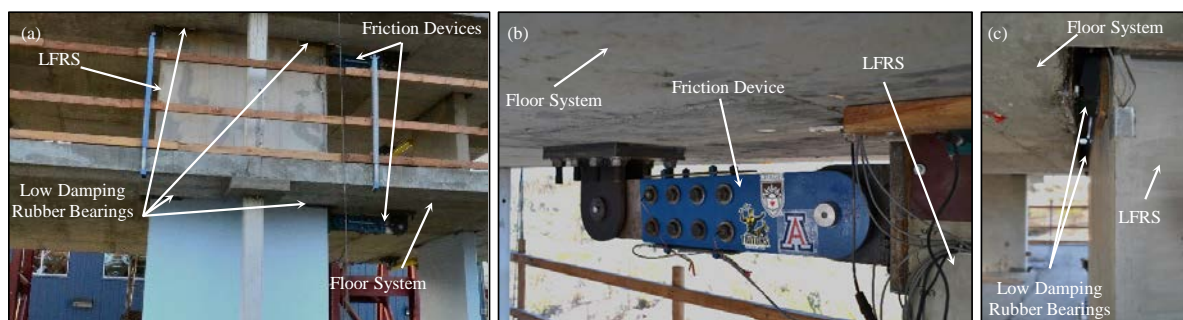

Figure 5. Implementation of the deformable connection on a rocking reinforced concrete shear wall structure at NEES@UCSD equipment site.

5 EXPERIMENTAL VALIDATION

To validate the response of the two configurations of the deformable connection, an experimental program was conducted using the NEES@Lehigh equipment site at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center (Tsampras and Sause 2015). The experimental set up included a portion of the twelve story reinforced concrete shear wall structure used in the numerical analysis. As shown in Figure 6a, part of the floor and part of the reinforced concrete shear wall were built in the laboratory. The components of the deformable connection were attached to these parts of the wall and floor. The objectives of the experimental program were to demonstrate the feasibility of the deformable connection for full-scale seismic demands from the twelve story building structure, to assess the process for installing the components of the deformable

connection and to validate the performance of the deformable connection under sinusoidal displacement histories at various frequencies and amplitudes and also under displacement histories that represent expected seismic deformation demands.

Figure 6b shows the test setup and specimen for the first configuration, including the wall and floor (without the concrete), the buckling restrained brace (from Star Seismic® LLC), and the steel reinforced low damping rubber bearings. Figure 6c shows the second configuration including the friction device (developed at Lehigh University) and the carbon fiber reinforced rubber bearings (from DYMAT™, INC). In Figure 6d, e the BRB and the FD are presented in more detail. In the test set up, relative horizontal motion of the floor with respect to the shear wall is applied resulting in cyclic axial deformation of the limited-strength load-carrying hysteretic components and shear deformation of the RB.
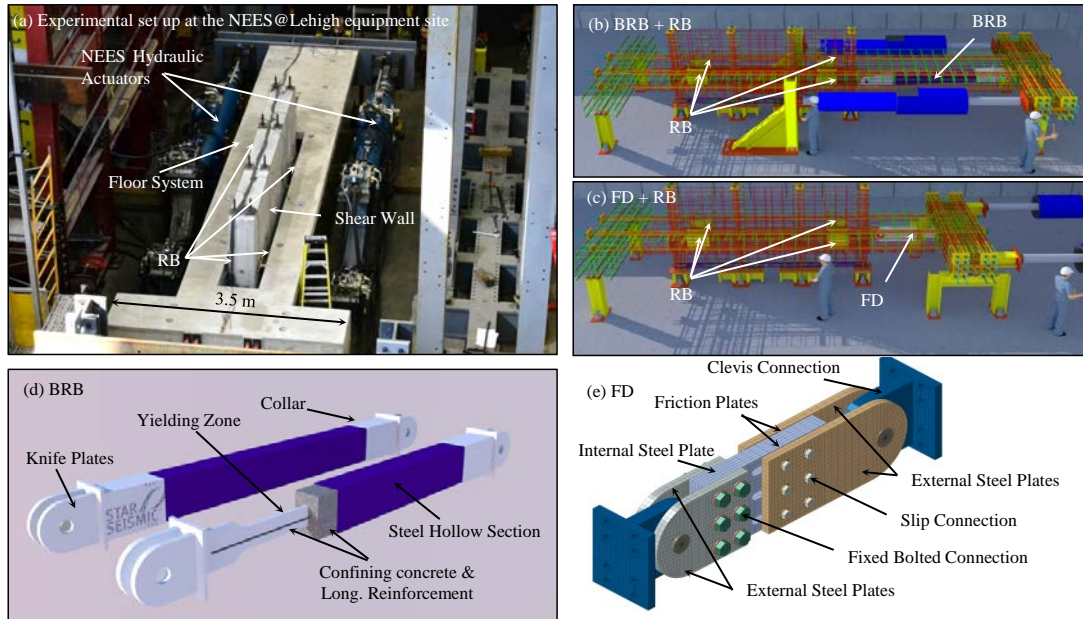

Figure 6. Experimental set up at NEES@Lehigh equipment site and the limited strength load carrying hysteretic components of the deformable connection.

The results from the experimental program showed that the design of the two configurations of the deformable connections are feasible. Figure 7a shows the experimental force–deformation response of the first configuration (BRB+RB). It can be observed that the hysteretic response is stable under large deformations. Also, the attachments of the deformable connection to the wall and floor behaved as expected. The calibrated numerical model developed in OpenSEES is consistent with the experimental results as shown by comparing the force-deformation behavior of the connection in Figure 7a and the time history of the hysteretic energy dissipation in Figure 7b. Figure 7c shows the experimental force-deformation response of the second configuration (FD+RB) of the deformable connection. Also for this configuration, the hysteretic response was stable under large deformations. The agreement of the numerical model developed in OpenSEES with the experimental results is excellent as shown in Figure 7c, d. The experimental results confirm that the two configurations for the deformable connection are feasible and provide the expected response.
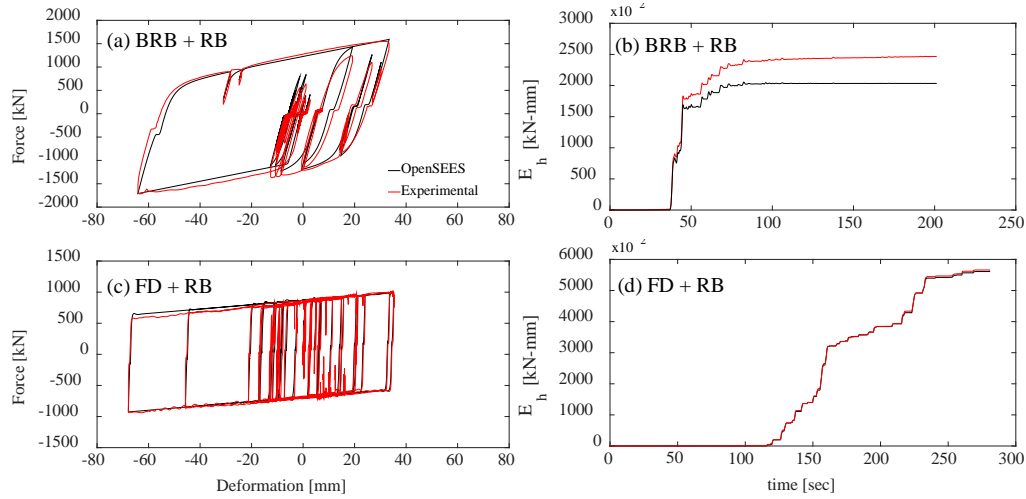
Figure 7. Experimental results of the two configurations of the deformable connection and calibration numerical models developed in OpenSEES.

6 CONCLUSIONS

Preliminary numerical analysis shows that using deformable connections between the LFRS and GLRS can result in reduced seismic structural response of the LFRS and GLRS of an earthquake-resistant building system. The objectives for using the deformable connection are the following:

1. Limit the forces transferred from the GLRS to the LFRS at each floor

2. Limit the floor accelerations (as a result of the limited force transfer)

3. Reduce the higher mode contribution to the structural response

4. Reduce the forces that develop in the LFRS

Details of two configurations of the deformable connection were presented. Experimental results showed that the hysteretic responses of the two configurations are stable under large deformations similar to the seismic demand for a twelve story building.

7 ACKNOWLEDGEMENTS

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