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# INVESTIGATION OF THE EFFECTIVENESS OF GROUND VIBRATION FORTIFICATION TECHNOLOGIES IN BUILDING SEISMIC DESIGN CODES

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## Abstract

Heng Zhang invented the seismograph as early as AD 132 and in the following 1890 years, the death toll from major earthquakes has remained high despite the increasing level of fortification of buildings against ground vibration in various countries around the world. In view of this, the authors of this paper investigate the effectiveness of ground vibration fortification technologies in building seismic design codes. The results show that: (1) there has been a longstanding misunderstanding that ground vibration is the main cause of building collapse during earthquakes so that buildings have been fortified only against ground vibration; (2) various vibration isolation and vibration reduction technologies have been generally accepted, but their actual function is limited to reducing the impact of ground vibration effects on buildings that already meet the seismic condition; (3) vibration-resistant reinforcement is generally accepted, and its function is limited to in-

creasing the ground vibration resistance of buildings that already meet the seismic condition; and (4) the seismic performance design goal is to change buildings from those that are susceptible to seismic damage those that are not. Therefore, these generally accepted technologies cannot actually achieve the seismic performance design goal. Based on the above four conclusions, the authors suggest that the seismic design code of buildings should add specifications for shear banding fortification and that areas where structures have been built or are planned should be divided into non-shear-banding zones and shear-banding zones. In this way ground vibration fortification can be effectively carried out for buildings in non-shear-banding zones, and both shear banding fortification and ground vibration fortification can be effectively carried out for buildings in shear-banding zones.

Keywords: tectonic earthquakes, ground vibration, shear banding, vibration isolation, damper, seismic conditions.

## Introduction

Compulsory education for citizens in Taiwan was extended from six to nine years in 1968, and based on the need to accommodate more students, a large number of standard buildings were built to serve as junior high schools as shown in Figure 1. During the 921 Jiji earthquake in 1999, Guangfu Junior High School in Taichung, Taiwan collapsed as shown in Figure 2. Therefore, the Taiwan Ministry of Education spent more than NT$40 billion after the 921 Jiji earthquake on the seismic reinforcement of school building structures, entrusting the National Center for Research on Earthquake Engineering (NCREE, 2009) to carry out the task.

Figure 1. Sanmin Junior High School in Hualien, Taiwan remained stable after the 921 Jiji earthquake of 1999 (Google Earth, 2020).

Note: The red line indicates the position of the first floor.

Figure 2. Guangfu Junior High School in Taichung, Taiwan suffered severe damage during the 921 Jiji earthquake of 1999 (Hsu, 2022).

After the 921 Jiji Earthquake, National Center for Research on Earthquake Engineering (NCREE, 1999) immediately revised the seismic design specifications, greatly increasing the specified ground vibration fortification level of building columns, beams, plates, and walls, assuming that vibration isolation pads and dampers could help reduce earthquake hazards. That is why vibration isolation pads and dampers were promoted in the revised code.

When designing a building, the structural technician must first analyze the ground vibration response through a structural analysis model, and the ground vibration response analysis requires an input ground vibration acceleration history for the design earthquake applied at the bottom ends of all columns in the model. Therefore, the bottom ends of all columns of the building model are set as fixed ends as shown in Figure 3.

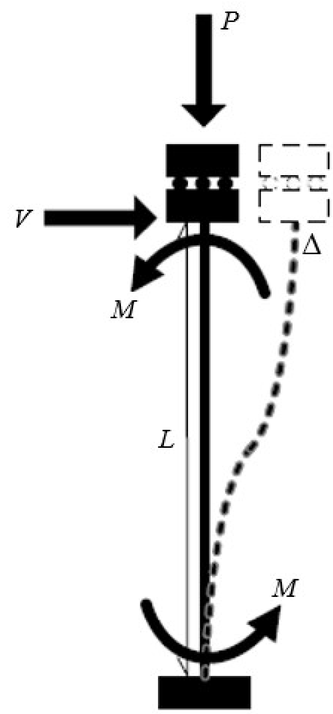


Figure 3. Schematic diagram for the bottom end of a column is set as the fixed end (Huang, 2014).

Since the design must achieve the seismic performance design goal, as long as the boundary conditions at these column ends continue to maintain their fixed end condition during the earthquake, the building should not collapse under the ground vibration of the design earthquake. However, the main effect of tectonic earthquakes is shear banding and ground vibration is a secondary effect. The energy associated with shear banding accounts for more than 90% of the total energy of the earthquake, whereas ground vibration accounts for less than 10% (Coffey, 2019). Therefore, if the performance design only ensures that a building will not collapse from ground vibration, it would likely still collapse from the shear banding effect.

By observing the buildings that have not collapsed in zones without shear-banding and the collapsed buildings in zones with shear-banding after previous earthquakes in Taiwan, Hsu (2022) defined the "seismic condition", or stable condition, when a building does not collapse during a tectonic earthquake as such that the fixed end condition set for the bottom ends of all columns in the original building design remains unchanged; and the "non-seismic condition", or unstable condition, occurs when a building does collapse during a tectonic earthquake because the fixed end condition set for the bottom ends of all columns in the original building design changes.

Based on the above definitions, it is possible to examine the buildings that use vibration isolation pads and dampers, *i.e.*, those with an increased ground vibration fortification level, in order to understand whether or not they meet the seismic performance design goal.

## Conditions Required for a Building to Increase its Ground Vibration Fortification Level

Figure 4 shows the force distribution of a building located in a non-shear-banding zone under the action of ground vibration acceleration. We can see that when the ground vibration fortification level increases, the cross-sectional area and amount of reinforcement of the structural elements, such as the columns, beams, panels, and walls of the building, also increase.

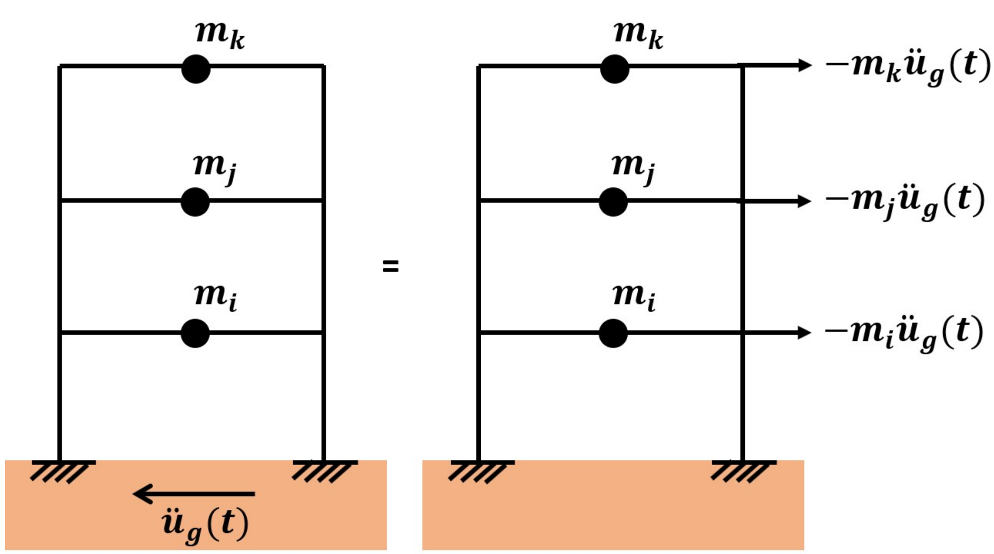


Figure 4. Schematic diagram for the force distribution of a building located in a non-shear-banding zone under the action of ground acceleration.

If a building is located in a non-shear-banding zone, by considering Figure 4 and the middle building of Figure 5, we can see that increasing the ground vibration fortification level only increases the ground vibration resistance of buildings, and this meets the seismic condition proposed by Hsu (2022). Since the horizontal ground surface remains horizontal, the continuous ground remains continuous, and the rigid ground remains rigid during a tectonic earthquake in non-shear-banding zones, buildings located in such zones will not tilt or collapse during tectonic earthquakes as long as they comply with the previous seismic design codes, and therefore they had already achieved the seismic performance design goal without increasing their ground vibration fortification level.

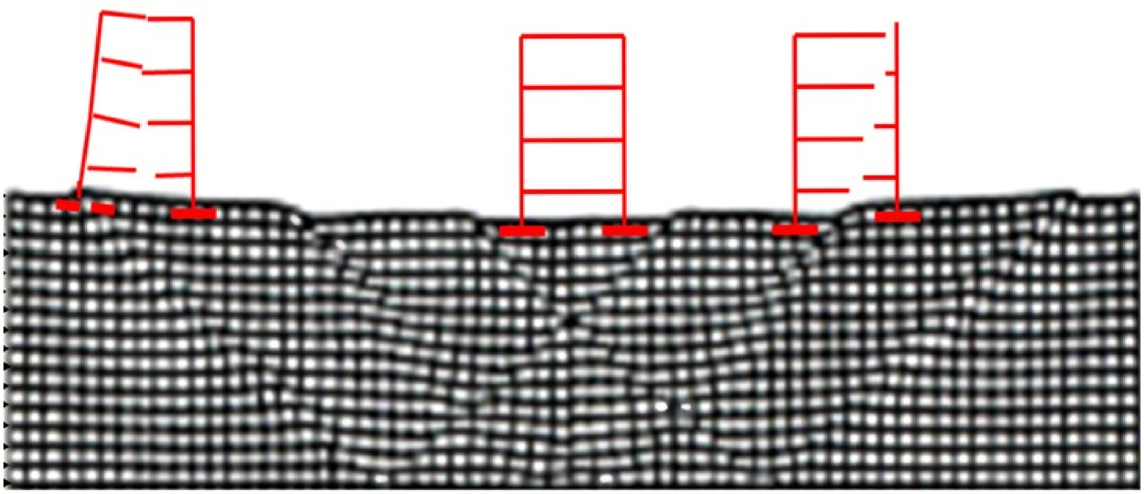

Figure 5. The collapse phenomena of buildings located in a shear-banding zone and non-collapse of buildings located in a non-shear-banding zone (Hsu et al., 2017).

Considering the buildings on the left and right of Figure 5, we can see that the ground vibration fortification level of the buildings located in the shear-banding zone is also increased but, in fact, this increase in the ground vibration fortification level is under the non-seismic (unstable) condition defined by Hsu (2022), and buildings in such zones will tilt or collapse during a tectonic earthquake because the horizontal ground surface cannot remain horizontal, the ground cannot remain continuous, and the ground cannot remain rigid. In other words, buildings located in shear-banding zones will still tilt or collapse due to the shear banding of future tectonic earthquakes, and regardless of how much the ground vibration fortification level is increased, the seismic performance design goal cannot be achieved.

## Inspection of Conditions Required for the Use of Vibration Isolation Pads

To date, scholars and experts in ground vibration disaster mitigation assume that isolating the ground vibration effect of tectonic earthquakes can help reduce the impact of ground vibration on building safety; thus, the current seismic design code for buildings has promoted the use of vibration isolation pads as shown in Figure 6.

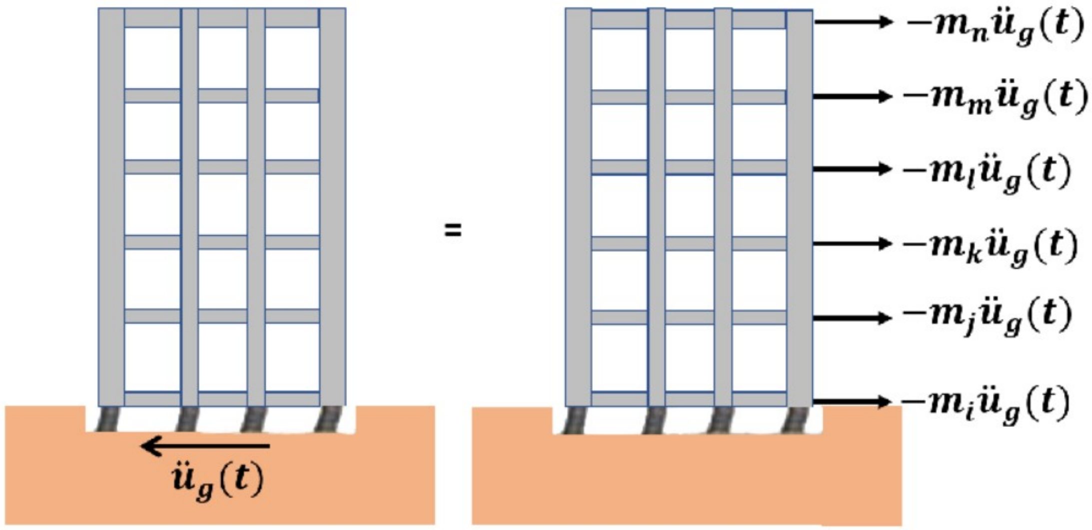


Figure 6. Schematic diagram for the force distribution of a building equipped with vibration isolation pads located in a non-shear-banding zone under the action of ground vibration acceleration.

When a building is located in a non-shear-banding zone, we can see from Figure 6 that the isolation of ground vibration in the non-shear-banding zone serves only to further reduce the impact of ground vibration on building safety under the seismic condition (stable building) defined by Hsu (2022). Figure 6 shows that the conditions required for the installation of vibration isolation pads are such that the horizontal ground surface remains horizontal, the continuous ground remains continuous, and the rigid ground remains rigid; thus, buildings that conform to the past seismic design code will not tilt or collapse during tectonic earthquakes. Therefore, the buildings located in non-shear-banding zones have already achieved the seismic performance design goal without the installation of vibration isolation pads.

When a building is located in a shear-banding zone, however, it can be seen by considering the buildings on the left and right of Figure 6 that the installation of vibration isolation pads can only isolate the effect of ground vibration under the non-seismic (unstable) condition defined by Hsu (2022). This is a problem because during an earthquake the horizontal ground surface cannot remain horizontal, the continuous ground cannot remain continuous, and the rigid ground cannot remain rigid; thus, the buildings will tilt or collapse during a tectonic earthquake. In addition, even if buildings located in shear-banding zones fully meet the requirements of the existing seismic design code, the horizontal shear of the vibration isolation pad will make the building more likely to tilt or collapse under the shear banding effect of a tectonic earthquake, and so the seismic performance design goal cannot be achieved in this manner.

Inspection of Conditions Required for the Use of Dampers

At present, scholars and experts in ground vibration disaster mitigation believe that dampers can reduce the impact of tectonic earthquake ground vibrations on buildings, and so the current seismic design code for buildings promotes the use of dampers as shown in Figure 7.

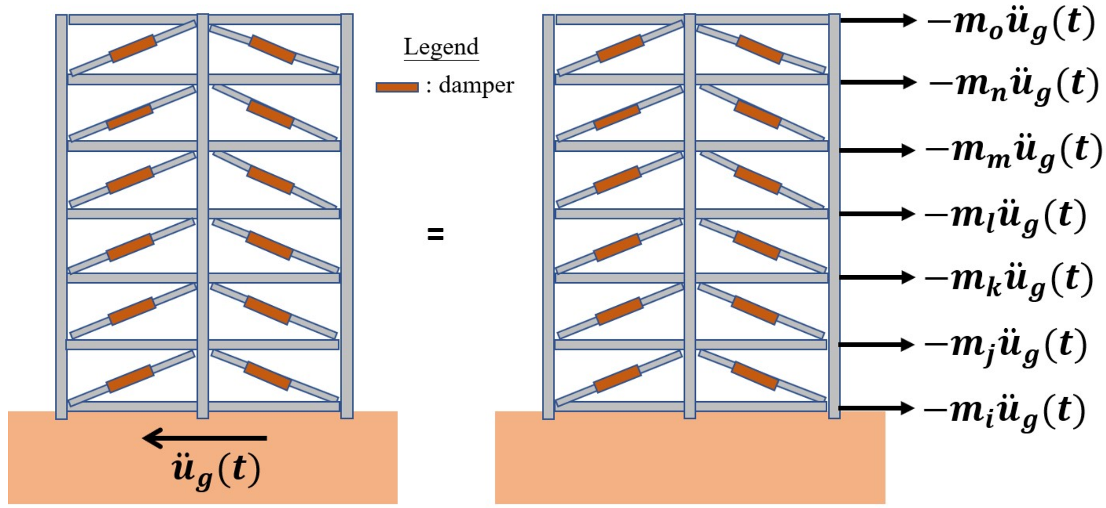


Figure 7. Schematic diagram for the force distribution of a building equipped with dampers located in a non-shear-banding zone under the action of ground vibration acceleration.

When a building is located in a non-shear-banding zone, it can be seen from Figure 7 that installing dampers to reduce the ground vibration effect only reduces the ground vibration under the seismic (stable) condition defined by Hsu (2022). From Figure 6, we can see that the conditions for the installation of dampers include that the horizontal ground surface remains horizontal, the continuous ground remains continuous, and the rigid ground remains rigid during a tectonic earthquake; thus, buildings that conform to the past seismic design specifications will not collapse during tectonic earthquakes. Therefore, the buildings located in the non-shear-banding zone can achieve the seismic performance design goal without the installation of dampers.

When a building is located in a shear-banding zone, however, by considering the buildings on the left and right of Figure 5, it can be seen that the installation of dampers can only reduce the impact of ground vibration under the non-seismic (unstable) condition defined by Hsu (2022). Due to the shear banding effect of a tectonic earthquake, the horizontal ground surface cannot remain horizontal, the continuous ground cannot remain continuous, and the rigid ground cannot remain rigid, and so the building will tilt or collapse. Therefore, the installation of dampers in buildings located in shear-banding zones will not only greatly increase the cost, but also does not change the non-seismic (unstable) condition of a building due to shear-banding to a seismic (stable) condition. Thus the performance design goal cannot be achieved.

## Results and Discussion

1) Shear bands are induced during tectonic earthquakes due to the localization of deformation of the ground, which in turn causes buildings to tilt or collapse. Structural dynamics scholars and experts often ignore the influence of shear banding in the identification of the causes of natural disasters, and so these identified causes often include underestimation of the effects the overall building weight, insufficient columns, walls, reinforcements, and stirrups, weak columns, and poor quality of concrete construction (Hsu, 2018).
2) When ground vibration is misidentified as the main cause of a tectonic earthquake disaster, amendments to the code for seismic design of buildings only increase the required ground vibration fortification level of the structural elements of a building. Therefore, although the cross-sectional area and the amount of reinforcement of the structural elements of future buildings will have increased significantly (see Figure 8), they will still tilt during future tectonic earthquakes (see Figure 9).

Figure 8. Excessive cross-sectional area and steel reinforcement resulting from the revised seismic design code after the 921 Jiji earthquake (Lin *et al*., 2022).

Figure 9. A new building nearing completion tilted severely after the 2016 Meinong earthquake (Hsu, 2022a).

3) For a tectonic plate subjected to continuous lateral compression, the strain softening when the strain enters deeply into the plastic range will cause the tectonic plate to lose its stability and symmetry, thereby inducing shear bands as shown in Figure 10 (Hsu, 1987). From Figure 10, we can see that the shear-banding displaced landform features of the tectonic plate include brittle fracture in the shear bands, discontinuity caused by shear banding, and uneven ground surface induced by the tilting uplift effect.

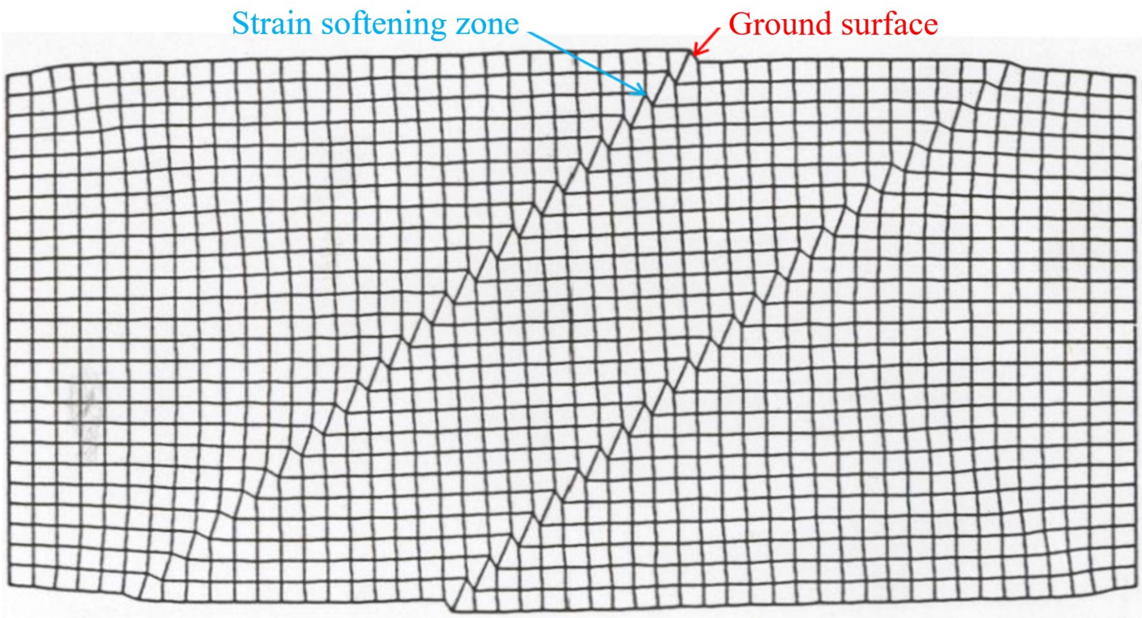


Figure 10. Shear bands and shear-banding displaced landform features induced in a tectonic plate under lateral compression (Hsu, 1987).

4) Since the shear-banding displaced landform features become more significant as the plate continues to undergo lateral compression, the building will still tilt or collapse because of the accumulated shear banding effect regardless of whether the ground vibration fortification level is increased by a hundred or even a thousand times.
5) The NCREE has continued to increase the ground vibration fortification level because the cause of seismic disasters have been misidentified as excessive ground vibration. The facts clearly indicate that when the seismic design code only fortifies against ground vibrations, it does not aid in improving seismic performance design and earthquake disaster mitigation, but also involves a large amount of wasted money.
6) Existing earthquake disaster mitigation technologies such as vibration isolation pads, dampers, and the seismic reinforcement of structures are only suitable for conditions such that the horizontal ground surface remains horizontal, the continuous ground remains continuous, and the rigid ground remains rigid during tectonic earthquakes. Therefore, the above-mentioned earthquake disaster mitigation techniques are only applicable to non-shear-banding zones and not to shear-banding zones. In summary, because the existing seismic design code does not define the seismic and non-seismic condition of a building nor distinguish non-shear-banding zones from shear-banding zones, tectonic earthquake disasters have continued to occur due to shear banding.

## Conclusions and Suggestions

Although scholars and experts from all over the world have studied the methods of earthquake mitigation for a long period of time and the ground vibration fortification level of buildings has continued to increase, the number of deaths from major earthquakes has remained high. In view of this, the authors of this paper draw the following four conclusions from this research:

1) Tectonic earthquakes are the most frequent kind of earthquake. Of these, tectonic earthquakes with a magnitude greater than 6.0 can induce building tilt or collapse. The main effect of tectonic earthquakes is shear banding, the energy of which accounts for more than 90% of the total energy, and the secondary effect is ground vibration, which accounts for less than 10%. It can be seen from this that the world has long misidentified the main cause for the collapse of buildings during tectonic earthquakes as excessive ground vibration, resulting in the developed seismic design codes only specifying fortification against ground vibration.
2) Although the world has generally accepted vibration isolation and vibration reduction technologies, the application conditions of these two technologies are that the building is in the seismic (stable) condition de-

fined by Hsu (2022), and so their actual function has only been to further reduce the impact of ground vibration on buildings that would not have tilted or collapsed in any case.

3) The application conditions of the generally accepted vibration-resistant reinforcement technology are that the building is in the seismic condition defined by Hsu (2022), and so its actual function has been only to further increase the resistance of ground vibration on buildings that would not have tilted or collapsed in any case.
4) At present, the seismic design of buildings has tended to be based on performance seismic design but its goal should be to change a building from a seismically unstable building to a seismically stable building. The application of technologies based only on vibration isolation, vibration reduction, and vibration resistance cannot achieve the seismic performance design goal.

The author provides the following two suggestions in order to make future earthquake disaster reduction technology more effective:

1) The seismic design code should include specifications for shear banding fortifications. The boundary condition in the design of a building, including that the bottom end of each column is fixed, will only apply when buildings are fortified against shear banding due to a tectonic earthquake.
2) The seismic design code should stipulate that districts, counties, and cities should be divided into non-shear-banding zones and shear-banding zones. In this way ground vibration fortification can be carried out for the non-shear-banding zones and both shear-band fortification and ground vibration fortification can be carried out for the shear-banding zones.

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