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CAUSES AND TYPES OF BUILDING FAILURE DUE TO TECTONIC EARTHQUAKES

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Abstract

The revisions of the seismic design codes for buildings often overlook the actual causes and types of building failure during tectonic earthquakes, leading to the recurrence of similar damage in subsequent seismic events. For this reason, the actual causes and types of building failure due to tectonic earthquakes were investigated in this study, with the following main findings: (1) shear banding, but not ground vibration, due to tectonic earthquakes changes the seismic conditions of buildings from seismic to non-seismic, making shear banding the cause of building failure during tectonic earthquakes rather than ground vibration; (2) shear banding induces plastic strain softening and tilting-uplift effects, resulting in collapse-type failure of buildings; (3) the seismic reinforcement of school buildings is based on the results of pushover tests and analyses, the cause of their failure is attributed to ground vibration, and failure is of the weak column-strong girder type, which is distinct from collapse-type failure; (4) vibration isolation, shock absorption, and vibration resistance technologies enhance the vibration resistance of buildings under seismic conditions, but they cannot improve design performance when shear banding due to tectonic earthquakes is involved. Based on these findings, we suggest that revisions to the seismic design codes should incorporate the actual causes and types of building failure due to tectonic earthquakes to ensure that buildings have enhanced seismic performance.

Keywords: tectonic earthquake, ground vibration, shear banding, seismic condition, performance design, pushover.

Introduction

Construction and Planning Agency under the Ministry of Interior, Taiwan, promulgated the first version of the seismic design code for buildings in 1974. However, buildings designed in accordance with the code (Construction and Planning Agency under the Ministry of Interior, Taiwan, 2011) have continued to experience failure during subsequent tectonic earthquakes. The seismic design code for buildings was revised in 1982, 1997, 1999, 2005, and 2011 to increase the ground vibration fortification level. Consequently, the horizontal ground vibration resistance has increased by approximately 100% since 1974 (Su, 2016).

As shown in Figure 1, the girders and columns of buildings designed according to the most recent seismic design codes have large cross-sectional areas and amounts of steel bars. However, despite the implementation of the latest code, building failures occurred during the 2016 Meinong earthquake, as illustrated in Figure 2. Thus, the following key aspects must be addressed before revising seismic design codes:

1) the definition of seismic conditions and non-seismic conditions of buildings;
2) the difference between the failure type of school buildings caused by the 921 Jiji earthquake and that produced by pushover tests and analyses;
3) the conditions required for the application of vibration isolation, vibration reduction, and vibration resistance technologies;
4) the status of the alignment of ground vibrations with the constitutive elements contributing to building failures.

Figure 1. Increase in the cross-sectional area and number of reinforcement girders, columns, and girder-column joints due to the increase in ground vibration fortification levels (Hsu, et al., 2023).

Figure 2. Failure in a building that complied with the latest seismic design code during the 2016 Meinong earthquake in Taiwan (Hsu, 2022a).

Failure Types of Buildings in Tectonic Earthquakes

According to Hsu (2022b), building failures due to tectonic earthquakes occur as a result of a shift in the designed boundary conditions of the building from seismic conditions to non-seismic conditions. Seismic conditions arise when the ground where the bottom ends of the building columns remain horizontal, continuous, and rigid during tectonic earthquakes. On the other hand, non-seismic conditions arise when the ground cannot maintain its horizontal, continuous, and rigid characteristics during earthquakes.

The main reason for the change in boundary condition at the bottom ends of building columns from seismic to non-seismic conditions is continuous lateral compression exerted on the tectonic plate. When the strain goes deep into the plastic range, the tectonic plate loses stability and symmetry due to strain softening (Drucker, 1950; Hsu, 1987; Rudnicki and Rice, 1975; Rice, 976). Subsequently, the deformation is localized, leading to the effects of shear banding and tilting-uplift (Hsu, 2022a).

Within the shear band zone, Hsu (2022b) addressed that even slight changes in the seismic conditions of the building to non-seismic conditions can result in slab cracking, as depicted in Figure 3(a). Moderate changes from seismic conditions to non-seismic conditions can cause the building to tilt and subside, as shown in Figure 3(b). Finally, significant changes from seismic conditions to non-seismic conditions can lead to the complete collapse of the building, as illustrated in Figure 3(c).

(a) Slab cracking when the seismic condition of a building changes slightly to a non-seismic condition (Hsu, 2022b)

(b) Tilting and subsidence of a building when the seismic condition of the building changes moderately to a non-seismic condition (Hsu, 2019; Hsu, 2022b)

(c) Fall and collapse of a building when the seismic condition of a building changes highly to non-seismic (Zhao, 2020; Hsu, 2022b)

Figure 3. Different types of building failure induced by different degrees of changes in seismic conditions.

Comparison of Actual School Building Failure and that Assessed by Pushover Tests and Analyses

Following the 921 Jiji earthquake, the Ministry of Education in Taiwan allocated more than NT$40 billion to ensure the safety of school buildings against future tectonic earthquakes. To achieve this, the National Center for Research on Earthquake Engineering (NCREE) was commissioned to develop seismic design methods specifically for school buildings. Subsequently, the seismic reinforcement plan for school buildings was implemented, the seismic design methods being based on the results of pushover tests and analyses (Hsu, 2022b). Important aspect are summarized below.

Actual Failure of a School Building During the 921 Jiji Earthquake

Figure 4 shows the collapse failure of the Guangfu Junior High School building in Nantou, Taiwan, during the 921 Jiji earthquake. The figure indicates that during the failure of the building, the original seismic conditions in the design changed to non-seismic conditions because of shear banding. Consequently, the ground where the bottom ends of all the columns were situated experienced undulations caused by the uneven effects of plastic strain softening and tilting-uplift within the shear banding zone. Once all the girders and columns were severely fractured, the building experienced collapse failure.

Figure 4. Collapse failure of the Guangfu Junior High School building in Nantou, Taiwan during the 921 Jiji earthquake (Hsu et al., 2023).

Failure of the School Building Assessed Through a Pushover Test

The seismic reinforcement method for school buildings, as provided by the NCREE, is based on pushover test results for school buildings (Hwang, 2009). Figure 5 demonstrates that the type of failure observed in a pushover test is weak column–strong girder. Furthermore, Figure 5 shows that the original seismic conditions set in the design of a school building were consistently maintained during the pushover test. Because the school building did not experience failure under these seismic conditions, the weak column–strong girder type of failure in the pushover test was artificially imposed.

Figure 5. Imposed weak column-strong girder failure observed in the pushover test of a school building under seismic conditions (Hwang, 2009).

Failure Type of a Structural Analysis Model Assessed Through Pushover Analysis

The seismic reinforcement method for school buildings proposed by the NCREE also incorporates the pushover analysis results of structural analysis models of school buildings. Figure 6 shows that the seismic conditions initially established for the structural analysis model were consistently maintained throughout the pushover analysis. Since the structural analysis model of the school building did not fail under these seismic conditions, the weak column-strong girder failure observed in the pushover analysis was also artificially imposed.

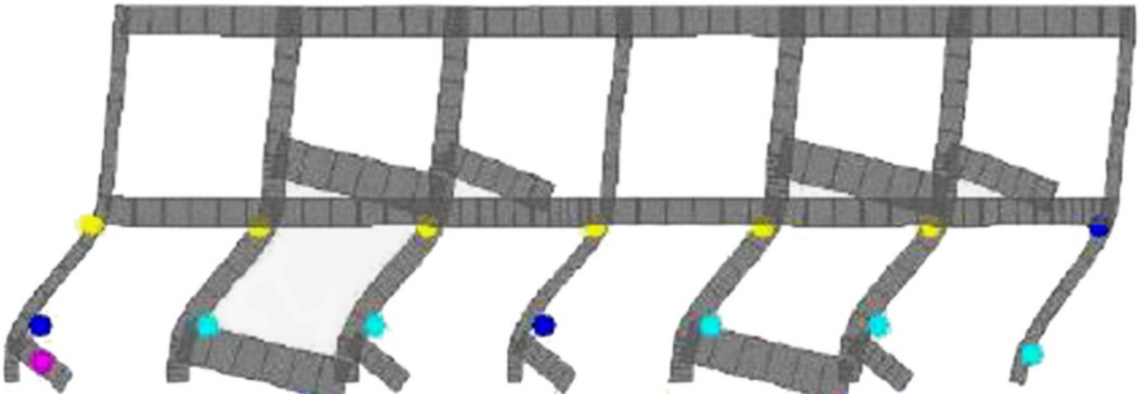

Figure 6. Continuity of seismic conditions in the structural analysis model of the school building assessed through pushover analysis (Hwang, 2009).

Conditions Required for the Application of Vibration Isolation, Vibration Reduction, and Vibration Resistance Technologies in Buildings

Although the current seismic design codes for buildings allow for the implementation of vibration isolation, vibration reduction, and vibration resistance technologies, they do not explicitly address the necessary conditions for utilizing these technologies. Therefore, a potential misconception among users may be that vibration isolation, vibration reduction, and vibration resistance technologies can be employed in building design under any conditions, thus guaranteeing protection against failure due to tectonic earthquakes. This section outlines the conditions required for applying vibration isolation, vibration reduction, and vibration resistance technologies to buildings.

Figures 7–9 present the respective conditions necessary for using vibration isolation, vibration reduction, and vibration resistance technologies in the seismic design of buildings. To utilize these technologies, all the bottom ends of the building columns must initially be set as fixed ends in the original designs. Consequently, the ground on which the building columns rest must remain horizontal, continuous, and rigid during tectonic earthquakes. In other words, employing vibration isolation, vibration reduction, and vibration resistance technologies necessitates that the seismic conditions set forth in the original design are consistently maintained during tectonic earthquakes.

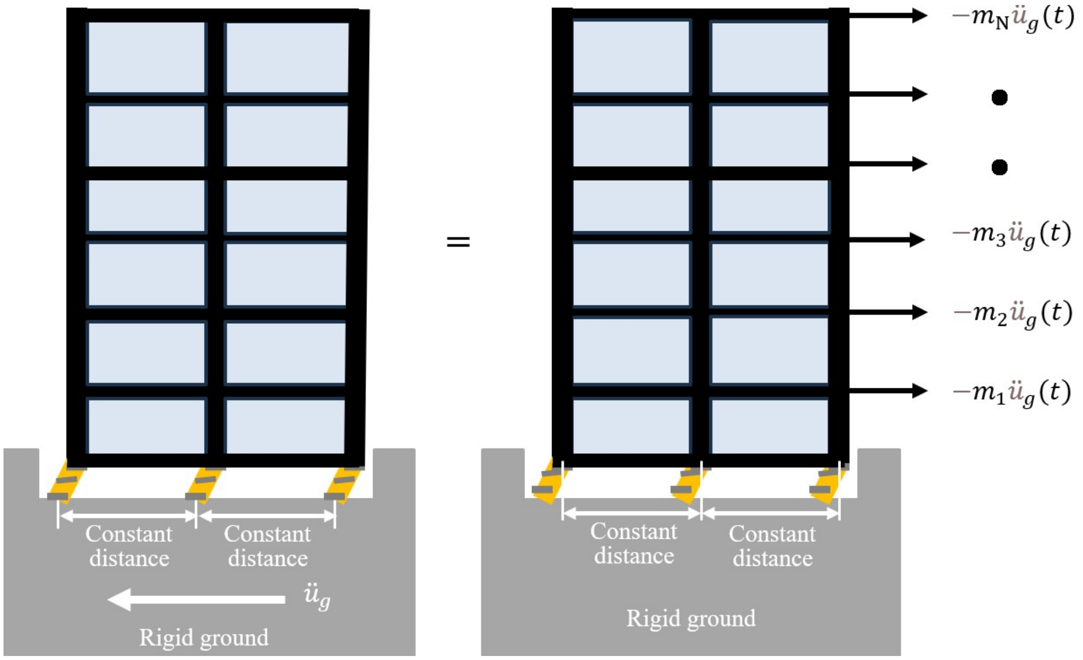

Figure 7. Conditions required for utilizing vibration isolation technology.

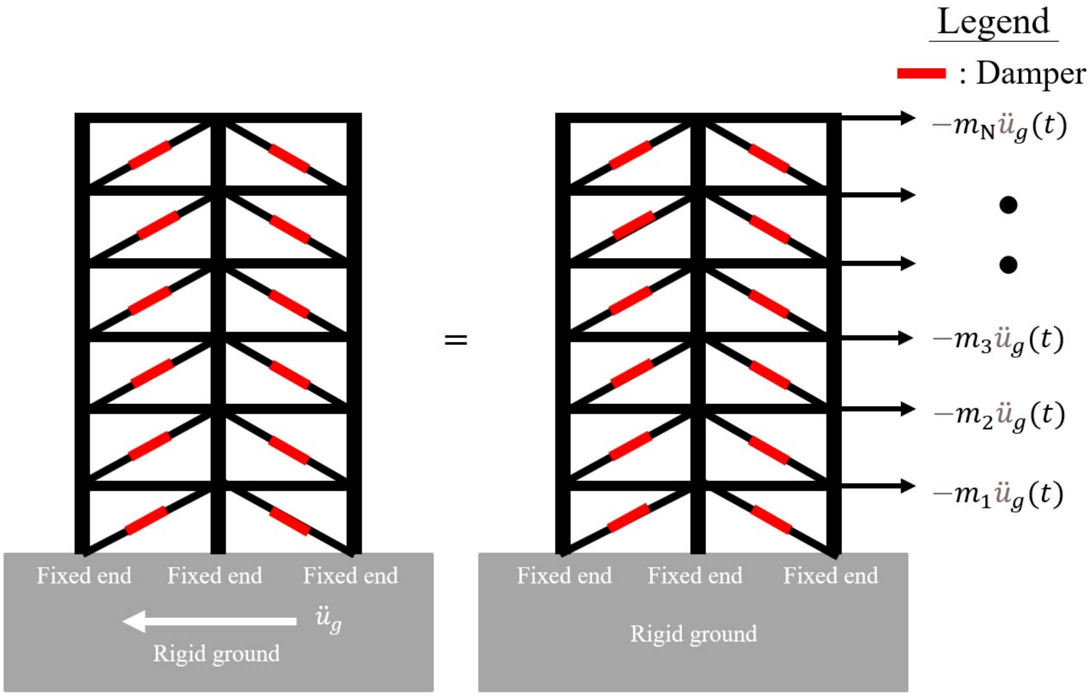

Figure 8. Conditions required for utilizing vibration reduction technology.

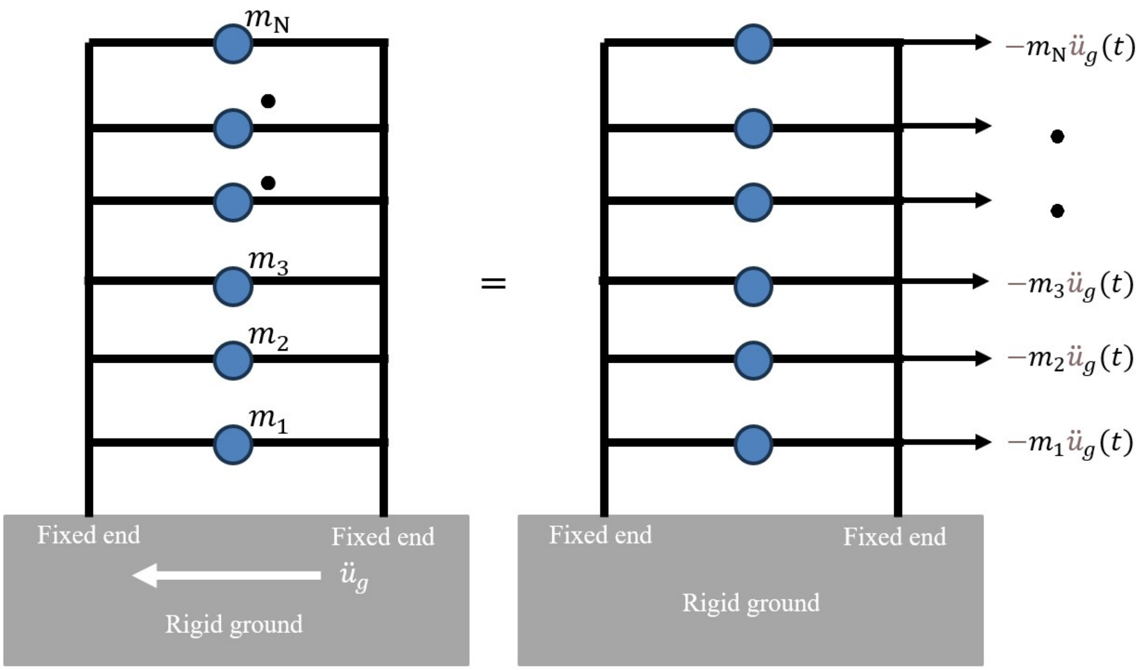

Figure 9. Conditions required for utilizing vibration resistance technology.

If a tectonic plate is divided into a shear banding zone and a non-shear banding zone, vibration isolation, vibration reduction, and vibration resistance technologies can only be applied in the non-shear banding zone, where the effects of only ground vibration are experienced, as illustrated in Figures 7–9.

Constitutive Elements of the Causes of Building Failure During Tectonic Earthquakes

The three constitutive elements of the causes of building failure during tectonic earthquakes are presented as follows:

1) Uniqueness

If and only if the hypothetical cause does exist, building failure occurs during tectonic earthquakes.

2) Entirety

If and only if the hypothetical cause does exist in some areas of a country, building failures during tectonic earthquakes will occur in these areas and their adjacent areas sharing the same hypothetical cause.

3) Comprehensiveness

If and only if the hypothetical cause does exist in some countries of the world, building failures during tectonic earthquakes will occur in these countries and their adjacent countries sharing the same hypothetical cause.

It is important to note that the causes of building failure must satisfy all three constitutive elements simultaneously. If a hypothetical cause fails to satisfy all three constitutive elements, it may not be the actual cause of building failure.

Verifying Whether Ground Vibration is the Cause of Building Failure

The existing seismic design codes for buildings only fortify ground vibration effects due to tectonic earthquakes. However, buildings designed in compliance with these codes still experience failure in shear banding of tectonic earthquakes. Furthermore, the seismic performance design objective of buildings (which includes not collapse under strong vibration, repairable under medium vibration, and remaining intact under mild vibration) cannot be achieved. This section discusses the verification of whether the ground vibration effect satisfies the three constitutive elements of the cause of building failure during tectonic earthquakes.

Verification of Whether the Ground Vibration Effect Satisfies the First Constitutive Element of the Cause of Building Failure During Tectonic Earthquakes

Concerning the ground vibration effect of tectonic earthquakes, the uniqueness element states that building failure will occur if and only if the hypothetical cause of the ground vibration effect does exist.

First, ground vibration energy accounts for less than 10% of the total energy associated with tectonic earthquakes, and the seismic design codes for buildings fortifies against this. Hence, building failure should not occur if the hypothetical cause of the ground vibration effect does exist in tectonic earthquakes. Second, failure occurs only in shear banding zones, indicating that the ground vibration effect is not the cause of building failure.

Verification of Whether the Ground Vibration Effect Meets the Second Constitutive Element of the Causes of Building Failure in Tectonic Earthquakes

Regarding the ground vibration effect in tectonic earthquakes, the entirety element states that if and only if the ground vibration effect does exist in certain areas of a country, building failure should occur in these areas of the country and their adjacent areas sharing the same hypothetical cause.

Buildings designed in accordance with existing seismic design codes are intended to be protected against ground vibrations. Hence, if the ground vibration effect of tectonic earthquakes does exist in certain areas, building failure should not occur in these and adjacent areas. Furthermore, building failure occurs only in areas when shear banding effects rather than ground vibration effects are present. Thus, the ground vibration effect does not satisfy the second constitutive element of the cause of building failure due to tectonic earthquakes.

Verification of Whether the Ground Vibration Effect Meets the Third Constitutive Element of the Cause of Building Failure in Tectonic Earthquakes

Concerning the ground vibration effect in tectonic earthquakes, the comprehensiveness element states that if and only if the ground vibration effect does exist in certain countries in the world, building failures should occur in these countries and their adjacent countries sharing the same hypothetical cause.

Based on the same reasoning as in the preceding paragraph, the comprehensiveness element of the cause of building failure can be established. Therefore, the ground vibration effect does not satisfy the third constitutive element of the cause of building failure in tectonic earthquakes.

Verifying Whether the Shear Banding Effect of Tectonic Earthquakes is the Cause of Building Failure

The conditions of buildings in the original design change from seismic to non-seismic conditions during shear banding in tectonic earthquakes. This section aims to verify whether the shear banding effect satisfies the three constituent elements of the cause of building failure in tectonic earthquakes.

Verification of Whether the Shear Banding Effect Meets the First Constitutive Element of the Cause of Building Failure in Tectonic Earthquakes

Concerning the shear banding effect of tectonic earthquakes, the uniqueness element states that building failure will occur if and only if the hypothetical cause of the shear banding effect does exist.

First, the energy associated with shear banding accounts for more than 90% of the total energy of tectonic earthquakes and is not considered in the seismic design codes for buildings. Hence, building failure occurs if shear banding occurs during tectonic earthquakes. Second, failure occurs only under the shear banding effect. Thus, shear banding is the cause of building failure.

Verification of Whether the Shear Banding Effect Meets the Second Constitutive Element

Regarding the shear banding effect in tectonic earthquakes, the entirety element states that if and only if the shear banding effect does exist in certain areas of a country, building failure should occur in these areas of the country and their adjacent areas sharing the same hypothetical cause.

Since building failure occurs only under the shear banding effect during tectonic earthquakes, it is evident that if the shear banding effect is present, building failure will occur in the affected areas. Therefore, the shear banding effect satisfies the second constitutive element of the cause of building failure during tectonic earthquakes.

Verification of Whether the Shear Banding Effect Meets the Third Constitutive Element

Concerning the shear banding effect in tectonic earthquakes, the comprehensiveness element states that if and only if the shear banding effect does exist in certain countries in the world, building failures should occur in these countries and their adjacent countries sharing the same hypothetical cause.

Based on the same reasons provided in the previous point in this section, the comprehensiveness of the causes of building failure is valid. Hence, the shear banding effect satisfies the third constitutive element of the cause of building failure due to tectonic earthquakes.

Comparison and Discussion of Results

1) In shear banding, the stick-slip phenomenon occurs repeatedly due to the change of frictional resistance over time (Figure 10). The tectonic plate decelerates during the stick phase and accelerates during the slip phase, inducing ground vibrations (Figure 11). As the shear banding effect accounts for more than 90% of the total energy of tectonic earthquakes while ground vibration accounts for less than 10% (Coffey, 2019), it is evident that the primary effect of tectonic earthquakes is the shear banding effect, with the ground vibration effect being secondary.

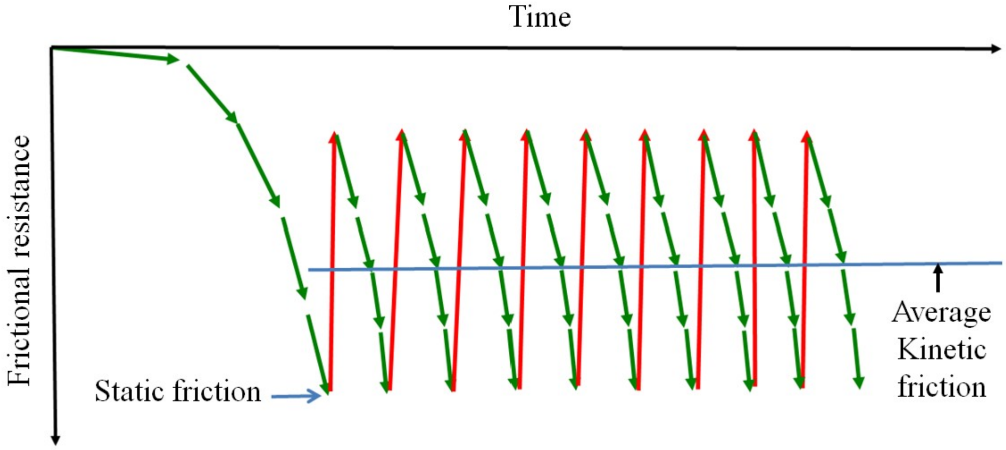

Figure 10. Stick–slip phenomenon in shear banding (Lambe, 1969).

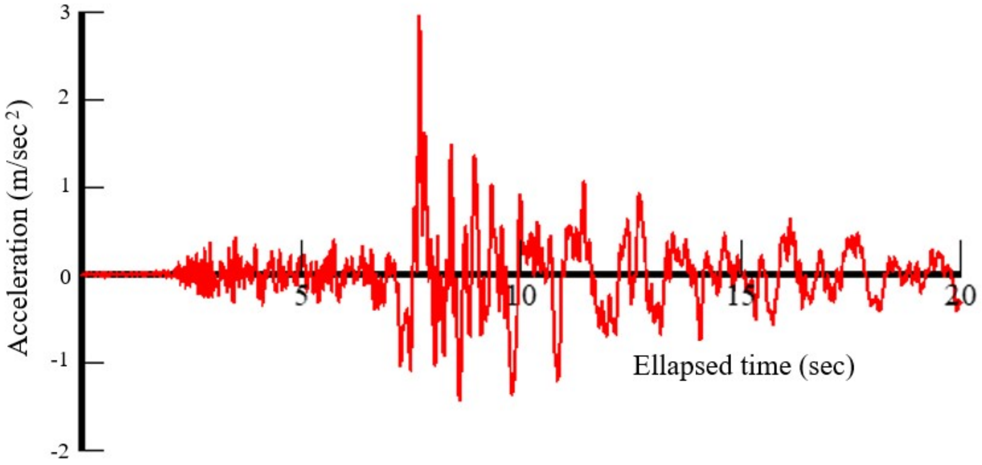

Figure 11. Ground acceleration time-history curve recorded using a seismometer (Hsu, 2018).

2) In the past, scholars and technicians attributed building failure during tectonic earthquakes to ground vibrations without proper evidence. Based on the evidence presented in this paper, it is clear that building failure in tectonic earthquakes is caused by shear banding, not ground vibration.

3) In the 921 Jiji earthquake, the collapse failure of Guangfu Junior High School occurred under non-seismic conditions, while the physical school building and the structural analysis model failed under seismic conditions. Thus, the collapse failure of Guangfu Junior High School differs significantly from the type of weak column-strong girder failure obtained from pushover tests and analyses. Therefore, the results of the pushover tests and analyses do not align with the actual requirements.

4) Although the current seismic design codes for buildings permit the use of vibration isolation pads and dampers, the conditions for their implementation require that the ground where the bottom ends of building columns are located remains horizontal, continuous, and rigid during tectonic earthquakes. In other words, the seismic conditions of the building must be consistently maintained during such events. Under these conditions, the installation of vibration isolation pads and dampers serves to enhance the ground vibration fortification level of the building, but does not guarantee the safety of buildings equipped with such measures when shear banding due to tectonic earthquakes occurs.

Conclusions and Suggestions

The previous revisions of the codes for the seismic design of buildings focused solely on improving the ground vibration fortification level under seismic conditions without considering the actual causes and types of building failure. Despite the continuous increase in ground vibration fortification levels in accordance with the latest seismic design specifications, buildings designed to meet these codes continue to fail during tectonic earthquakes. Hence, based on the study of the causes and types of building failure in tectonic earthquakes, the authors draw the following four conclusions:

1) Pushover tests and analyses are theoretically based on ground vibrations and invoke a weak column–strong girder failure type. However, this failure type not only differs from the actual collapse type observed in the failure of Guangfu Junior High School during the 921 Jiji earthquake, but is also not in accord with the seismic design code for buildings.

2) During the 921 Jiji earthquake, the mode of school building failure was induced by highly non-seismic conditions resulting from the tilting-uplift effect of shear banding. By contrast, neither the physical school building nor the structural analysis model in the pushover test and analysis experienced a change in the seismic conditions set in their original designs during the test and analysis. Therefore, the weak column–strong girder failure type obtained from the test and analysis did not align with the actual requirements.

3) Shear banding is the primary effect of tectonic earthquakes, while ground vibrations are secondary. The seismic design codes for buildings have already recommended fortification against ground motions, and the seismic conditions of buildings remain unchanged during ground vibrations. Therefore, ground vibrations cannot be considered the cause of building failure during tectonic earthquakes. Furthermore, based on the three constitutive elements of the cause of building failure in tectonic earthquakes, the cause of building failure due to tectonic earthquakes is shear banding, not ground vibration.

4) Although the current seismic design codes for buildings allow the application of technologies such as vibration isolation, vibration reduction, and vibration resistance, the prerequisite is that the seismic conditions set in the original design of the buildings must be continuously maintained during tectonic earthquakes. However, during shear banding due to tectonic earthquakes, the seismic conditions of buildings incorporating these technologies shift to non-seismic conditions. As a result, the design objective of achieving seismic performance cannot be fulfilled.

Based on the above four conclusions, the authors suggest the following measures for preventing building failure due to tectonic earthquakes:

1) The failure types of physical buildings and structural analysis models revealed by the test and analysis methods used in seismic design must align with the failure types observed in physical buildings after tectonic earthquakes.

2) The seismic design code for buildings must recommend strategies for fortification against shear banding due to tectonic earthquakes.

By adopting the proposed measures, the seismic conditions of buildings can be consistently maintained during shear banding due to tectonic earthquakes, thereby preventing the recurrence of failures such as slab cracks, tilting and subsidence, and collapse induced by shear banding.

References

Coffey, J., “What are the Different Types of Earthquakes?” Universe Today, Space and astronomy news, Website: https://www.universetoday.com/82164/types-of-earthquakes/, 2019

Construction and Planning Agency, Ministry of the Interior, “Seismic design specifications of buildings and commentary,” 2011

Drucker, D. C., “Some implications of work hardening and ideal plasticity,” *Quarterly of Applied Mathematics*, Vol. 7, No. 4, pp. 411-418, 1950

Hsu, S. E., “This building in Taipei repeats its history of tilting 33 years ago during the Hualien earthquake,” Chungshi News Network, Website: https://www.chinatimes.com/realtimenews/20190418002921-260405?chdtv, 2019

Hsu, Tse-Shan, *Capturing Localizations in Geotechnical Failures*, Ph.D. Dissertation, Civil Engineering in the school of Advanced Studies of Illinois Institute of Technology, 1987

Hsu, Tse-Shan, “The Major Cause of Earthquake Disasters: Shear Bandings,” A chapter in *Earthquakes-Forecast, Prognosis and Earthquake Resistant Construction*, Edited by Edited by Valentina Svalova, DOI: 10.5772/ intechopen.74718, Website: https://www.intechopen.com/chapters/59523, 2018

Hsu, Tse-Shan, “Plasticity Model Required to Protect Geotechnical Failures in Tectonic Earthquakes,” A chapter in *Earthquakes-Recent Advance, New Perspectives and Applications,* Edited by Walter Salazar, DOI: 10.5772/intechopen.107223, Website: https://www.intechopen.com/chapters/836702022a

Hsu, Tse-Shan, “Seismic Conditions Required to Cause Structural Failures in Tectonic Earthquakes,” A Chapter in *Natural Hazards-New Insight*s, Edited by Mohammad Mokhtari, DOI: 10.5772/intechopen.108719, Website: https://www.intec hopen. com/online-first/84810 2022b

Hsu, Tse-Shan, Chang-Chi Tsao, and Chihsen T. Lin, "Localizations of Soil Liquefactions Induced by Tectonic Earthquakes," *The International Journal of Organizational Innovation,* Vol.9, No. 3, Section C, pp. 110-131, 2017

Hsu, Tse-Shan, Yu-Chien Wu, Zong-Lin Wu, Tsai-Fu Chuang, “Investigation of the Effectiveness of Ground Vibration Fortification Technologies in Building Seismic Design Codes,” *International Journal of Organizational Innovation,* Vol. 15, No. 3, pp. 110-124, 2023

Hwang, Shyh-Jiann, E-paper of strengthening project office for school buildings, No. 2, National Center for Research on Earthquake Engineering, 2009

Lambe , T. William and Whitman, Robert V., *Soil Mechanics*, John Wiley & Sons, New York, pp. 65, 1969

Rice, J. R., “The Localization of Plastic Deformation," in *Theoretical and Applied Mechanics, Proceedings of the 14th International Congress on Theoretical and Applied Mechanics*, Delft, 1976, ed. W.T. Koiter, North Holland, Amsterdam, Vol. 1, pp. 207-220, 1976

Rudnicki, J. W. and Rice, J. R., “Conditions for the localization of deformation in pressure-sensitive dilatants materials,” *Journal of the Mechanics and Physics of Solids*, Vol. 23, pp. 371-394, 1975

Su, Chun-Yi, *Investigation of the Causes of Building Tilting and Collapse in Earthquakes*, Master Thesis, Department of Civil Engineering, Feng Chia University, 2016

Zhao, Y. T., “The Dongshing Building in Taipei collapsed during the 921 Jiji earthquake of 1999,” ETtoday net news, Website: https://www. ettoday.net/news/20200921/1810 526.htm, 2020