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[Technical Paper]

REPAIR OF EXPOSED COLUMN BASES BY RETIGHTENING OF ANCHOR BOLTS, AMOUNT AND BALANCE OF REPAIR

William Alexander RAMOS HERNANDEZ[1], Shotaro NAKADA[2] and Taiki SAITO[3]

[1] Student Member, M. Eng., Graduate Student, Department of Architecture and Civil Engineering, Toyohashi University of Technology, Aichi, Japan, william.alexander.ramos.hernandez.ri@tut.jp
[2] Member, Dr. Eng., Assistant Professor, Department of Architecture and Civil Engineering, Toyohashi University of Technology, Aichi, Japan, nakada.shotaro.lp@tut.jp
[3] Member, Dr. Eng., Professor, Department of Architecture and Civil Engineering, Toyohashi University of Technology, Aichi, Japan, saito.taiki.bv@tut.jp

ABSTRACT: This study evaluates the effects of amount and balance of repair in a gymnasium typical of Japanese schools. Several combinations of main shocks and aftershocks were evaluated. This study showed that a repair using partially retightened anchor bolts is not effective on the short span of the building, but it is effective in the long span, as long as the aftershocks are smaller than 25% of the main shock. The balance of repair does not reduce or amplify the out-of-plane deformation of the walls in the gymnasium, but it causes amplification of the in-plane deformation of the walls in the long span. Therefore, when repair by retightening of anchor bolts is performed, all column bases should be fully retightened as much as possible.

Keywords: *Exposed column base, Retightening of anchor bolts, Aftershock, Amount of repair, Balance of repair*

1. INTRODUCTION

In Japan, school gymnasiums are required to function as evacuation shelters during natural disasters[1)]. For example, gymnasiums often serve as temporary housing for evacuees and as centers for the distribution of supplies to affected populations. According to a nationwide survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT)[2)] in December 2022, 91.5% of public schools had been designated as evacuation shelters in accordance with the Basic Act on Disaster Management. Therefore, ensuring the structural safety of school gymnasiums following an earthquake is critically important.

Surveys conducted by MEXT in Fukushima and Miyagi prefectures[3)] showed that approximately 70% of schools used their gymnasiums as the main evacuation facility during disasters. In Japan, these gymnasiums are typically constructed using steel frames, to maintain large interior spaces without columns. The perimeter columns are generally supported by exposed column bases[4)]. Therefore, special attention must be given to the structural safety of exposed column bases in order to ensure the safety of school gymnasiums.

Japanese seismic design is based on the principle of ductile behavior. Structures are designed to have plastic deformation without a sudden loss of strength. In the case of exposed column bases, design guidelines specify that plastic hinges should form either in the column itself (column hinge) or on the anchor bolts (column base hinge)[5)]. On the other hand, when exposed column bases are designed to fail through anchor bolt shear rupture or cone-shape failure, a sudden loss of strength can occur. Experiences from other countries like the United States has shown that even in countries where such brittle failure is allowed, its use is generally discouraged[6)].

According to the AIJ Design and Fabrication Guide for Steel Column Bases[5)], the formation of a column base hinge requires the yielding of the anchor bolts. To guarantee this behavior, the loading conditions that cause anchor bolt yielding must occur before the conditions that cause shear rupture or cone-shape failure. In addition, anchor bolts should be embedded in the concrete foundation to a depth of at least 20 times their diameter. Compared to a column hinge, a column base hinge requires less material, because the base plate and anchor bolts do not need to provide the necessary strength to ensure the yielding of the column. On the other hand, the energy absorption capacity of a column base hinge is lower than that of a column hinge.

The mechanism of a column base hinge starts with lateral seismic loads transmitted to the column base as a bending moment. This moment induces tension forces in the anchor bolts. If the tension in the anchor bolts is higher than their yield strength, yielding occurs, producing residual deformation that remains even after the seismic loads end. This residual deformation prevents the base plate and anchor bolts from resisting additional loads until the column base is repaired. Because the anchor bolts are the primary components resisting seismic loads, repairing this type of exposed column base requires restoring the anchor bolts' ability to yield.

Previous studies have examined the possibility of repairing exposed column bases with residual deformation by retightening its anchor bolts. Tanaka et al.[7)] conducted cyclic loading tests on specimens until reaching an inter-story drift angle of 1/25. After unloading, the anchor bolts were retightened, and the exposed column base continued to resist additional seismic loads.

Baba et al.[8)] conducted cyclic loading tests on specimens until a residual anchor bolt deformation of 1% was reached. After retightening, the exposed column bases demonstrated sufficient strength and deformation capacity. However, the stiffness of the retightened specimens was smaller than before retightening, suggesting that the bond between the anchor bolts and the concrete was not fully restored.

Nakada et al.[9)] investigated the retightening of anchor bolts fixed to a jig using double nuts. The study compared the torque required to retighten anchor bolts with and without anticorrosive coating. The study also compared the torque required to retighten new and corroded anchor bolts. The results indicated that anchor bolts with anticorrosive coating required lower torque than those that were corroded, therefore confirming the superior workability of anchor bolts with anticorrosive coating.

Other research has considered retightening anchor bolts in all exposed column bases of a structure as a repair strategy. Lin et al.[10)] conducted a dynamic analysis on two low rise buildings and demonstrated that fully retightened anchor bolts are effective in restoring seismic performance.

The studies described above focused on either individual column bases or on buildings where all column bases were repaired uniformly. Additionally, in each case, the anchor bolts were fully retightened. However, surveys following the 1995 Kobe Earthquake[11)] and the 2011 Tohoku Earthquake[12)] reported significant damage to exposed column bases, including lateral buckling of anchor bolts, damage to base plates, and severe deterioration of grooves that sometimes prevented retightening[13)]. Similar issues have been observed outside Japan. For example, a report by the Minnesota Department of Transportation[14)] documented extensive damage in exposed column bases supporting towers and other roadside structures. These findings indicate that repair by fully retightening anchor bolts cannot always be guaranteed.

In many cases, anchor bolts in exposed column bases may only be partially retightened, due to damage to the grooves or the shaft. Moreover, even when it is possible to fully retighten the anchor bolts, it might not be feasible for all exposed column bases in a building. Such partial or unbalanced repair could introduce unexpected structural effects, potentially increasing column base and wall deformations when an aftershock comes. Despite this, existing studies have not addressed the influence of the amount and balance of repair in the response of a building.

This study addresses this lack of research by investigating the effects of the amount and balance of repair of exposed column bases in a school gymnasium. Time-history analyses were performed under various combinations of main shocks, aftershocks, amounts of repair, and balance of repair. The effects of repair were evaluated in each structural direction, and were compared to an unrepaired condition to identify potential amplification of the column base and wall deformations. The scope of the study is limited to school gymnasiums with a structural characteristics similar to the building in this study.

2. METHODOLOGY

2.1 Gymnasium model

The analytical model of the gymnasium is shown in Fig. 1. It is based on the "Type S" from the Manual for Seismic Retrofitting of School Facilities[4)], which represents a typical school gymnasium in Japan. The structure is a 6.3 m high steel frame, supported by 26 exposed column bases.

The analysis was performed using the software STERA 3D[15)]. Beams and columns were modeled as linear elements that resist axial forces and bending moments. Due to the software limitations, the geometry was simplified by flattening the roof and removing the braces. The roof was modeled as flexible. Because the walls are non-structural, their stiffness was excluded from the analysis.

2.2 Exposed column base model

The exposed column base, as presented in Fig. 2, consists of a H-shaped steel column, supported on a base plate anchored to the foundation using anchor bolts. The base plate measures 350 x 350 x 40 mm, and is anchored to a concrete foundation using four anchor bolts type ABR400 size M16, with an embedding depth l_b of 320 mm and a spacing of 170 mm[4)]. The connection between the column and base plate was assumed to be rigid, and the bending deformation of the base plate was neglected.

The exposed column bases were designed to form a column base hinge. In addition, they are modeled as rotational springs with a bilinear slip model. Their initial stiffness (K_0), secondary stiffness (K_1), yield moment (M_y), and yield angle (θ_y) are given by Eqs. (1)–(4)[5)] and Table 1.

$$K_0 = E \cdot n \cdot A \cdot (d_t + d_c)^2 / 2l_b \tag{1}$$

$$K_1 = 0.02 \cdot K_0 \tag{2}$$

$$M_y = n \cdot A \cdot \sigma_y \cdot (d_t + d_c) + N \cdot d_c \tag{3}$$

$$\theta_y = K_0 / M_y \tag{4}$$

Where E is the Young's modulus of the anchor bolts, n is the number of anchor bolts on the tension side, A is the cross-sectional area of an anchor bolt, d_t is the distance from the column center to the anchor bolts in tension, d_c is the distance from the column center to the compression flange, l_b is the embedding depth of the anchor bolts, σ_y is the yield stress of the anchor bolts, and N is the vertical force acting on the exposed column base.

The hysteresis model of an exposed column base is shown in Fig. 3. The vertical axis shows the moment on the column base, M, while the horizontal axis shows the angle of the base plate relative to the concrete foundation, θ. θ_{MS} is the maximum angle obtained during the main shock analysis.

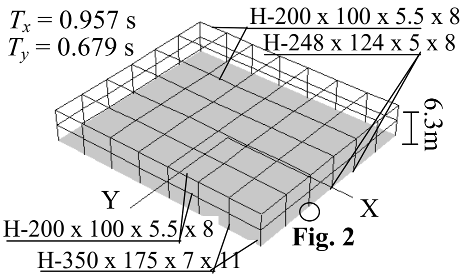


Fig. 1 Gymnasium model (STERA 3D)

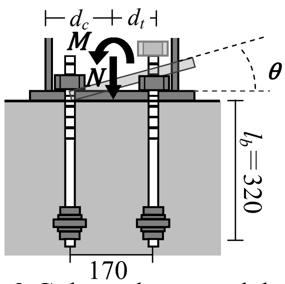


Fig. 2 Column base model

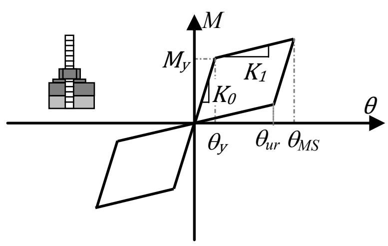


Fig. 3 Fully retightened model

Table 1 Properties of the exposed column base

n	A [mm^2]	d_c [mm]	d_t [mm]	l_b [mm]	E [N/mm^2]	σ_y [N/mm^2]	N [kN]	K_0 [kN.m]	K_1 [kN.m]	M_y [kN.m]	θ_y [rad]
2	166	175	85	320	2.06 x 10^3	235	48.8	7180	143.6	28.8	0.004

2.3 Main shocks and aftershocks

The main shocks considered in this study are shown in Fig. 4. Three earthquake records were used as input ground motions: a) the 1940 Imperial Valley earthquake (El Centro), b) the 1995 Hyogo-ken Nanbu Earthquake (Kobe), and c) the 1952 Kern County earthquake (Taft). For consistency, the ground motions were scaled so that the peak ground velocity (PGV) of each one was 100 cm/s.

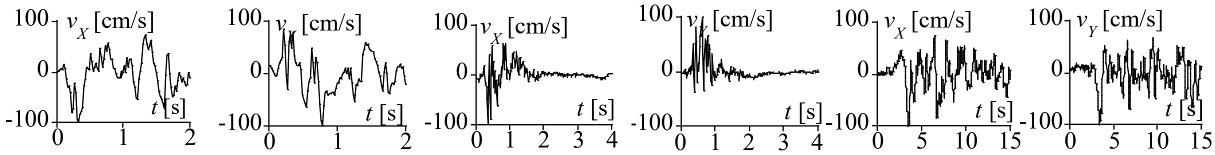
Aftershocks were generated using the same ground motions as the main shocks, but scaled in amplitude by an aftershock coefficient (β). As illustrated in Fig. 5, the aftershock coefficient β is defined as the ratio of the PGV of the aftershock to the PGV of the corresponding main shock[16]. In this study, four aftershock coefficients were considered: 0.25, 0.50, 0.75 and 1.00.

Each main shock and aftershock had two components: the X direction, parallel to the long span of the gymnasium, and the Y direction, parallel to the short span. When the main shock or aftershock is perpendicular to a wall, the corresponding deformation is referred to as “Out-of-plane”. Conversely, when the main shock or aftershock is parallel to a wall, the deformation is referred to as “In-plane”. For a wall bounded by two exposed column bases, the out-of-plane wall angle, R_j, and the in-plane wall angle, R_i, were calculated in this study using Eqs. (5)–(6), as illustrated in Fig. 6:

$$R_j = (D_{j1} - D_{j2}) / S = (\theta_{j1}H - \theta_{j2}H) / S = (\theta_{j1} - \theta_{j2}) \cdot (H / S) \quad (5)$$

$$R_i = (D_{i1} - D_{i2}) / H = (\theta_{i1}H - \theta_{i2}H) / H = (\theta_{i1} - \theta_{i2}) \quad (6)$$

Where D_j is the out-of-plane displacement caused by the out-of-plane rotation angle θ_j, D_i is the in -plane displacement caused by in-plane rotation angle θ_i, H is the height of the gymnasium and S is the span between the two columns. The bending deformation of the columns was neglected in this study because it was small compared to the displacement caused by anchor bolt yielding.



(a) El Centro, X (b) El Centro, Y (c) Kobe, X (d) Kobe, Y (e) Taft, X (f) Taft, Y

Fig. 4 Ground motions used in in this study

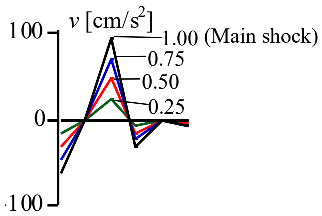
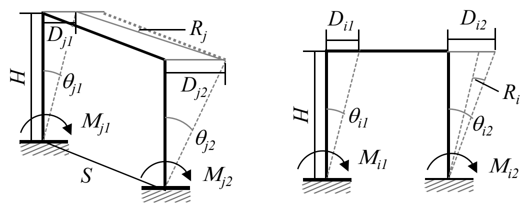


Fig. 5 Definition of β



(a) Out-of-Plane (b) In-Plane

Fig. 6 Definition of R

3. AMOUNT OF REPAIR

3.1 Analysis method for amount of repair

This chapter studies the effects of the amount of repair on the deformation of exposed column bases. The amount of repair γ, is defined as the ratio between the maximum residual deformation, δ_{max}, and the retightening length, δ_r, as expressed in Eq. (7)[16] and illustrated in Fig. 7:

$$\gamma = \delta_r / \delta_{max} \leq 1.0 \quad (7)$$

In this study, five values of γ were considered: 0.2, 0.4, 0.6, 0.8 and 1.0. For the purposes of this study, the construction error of bolts is not considered in the analysis.

Next, the analysis procedure is described. The analysis was conducted in two steps. First, a time-history analysis of the main shock was performed on a gymnasium model with fully retightened exposed column bases (the same model as shown in Fig. 3). Next, before applying the aftershock, the maximum positive and negative residual deformation angles θ_{ur}, obtained from the main shock analysis were multiplied by $1-\gamma$. This calculation provided the slip angle of the partially retightened column base model (Fig. 8). Using this slip angle, a time-history analysis of the aftershock was carried out, and the maximum rotational angle during the aftershock, θ_{AS} was determined.

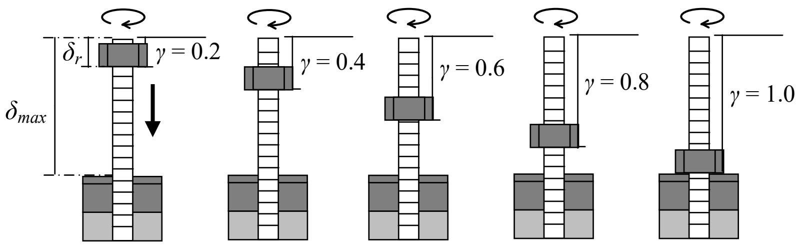


Fig. 7 Definition of amount of repair, γ

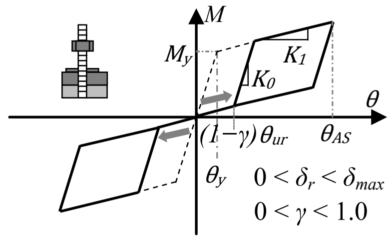


Fig. 8 Partially retightened model

3.2 Results

3.2.1 Relationship between aftershock angle (θ_{AS}) and amount of repair (γ)

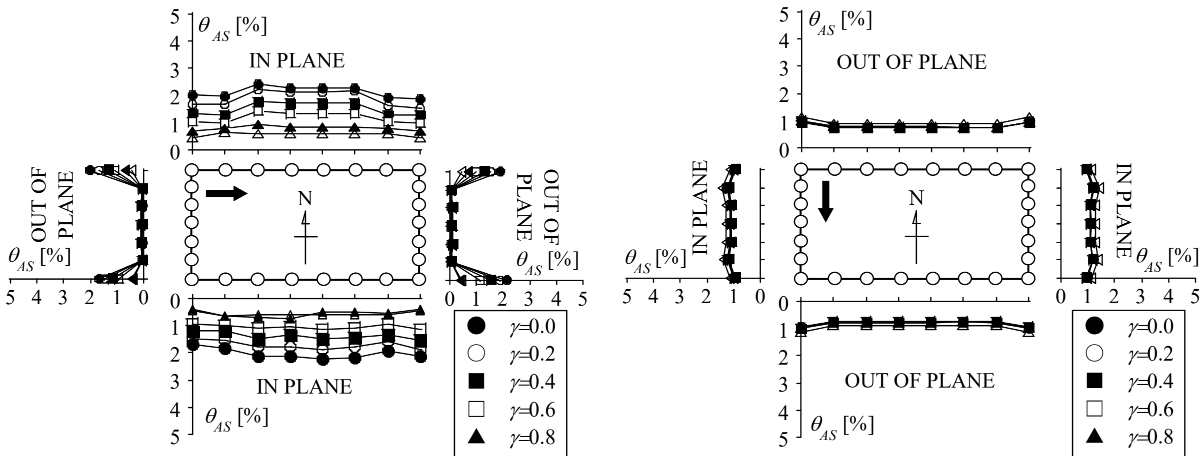
The distribution of the maximum rotational angle obtained from the aftershock analysis, θ_{AS} for all exposed column bases is shown in Fig. 9. The results are based on the Kobe earthquake with an aftershock coefficient $\beta = 0.25$. In the figure, the amount of repair γ is indicated by different markers. Figure 9(a) shows the X direction, while Fig. 9(b) shows the Y direction.

In the X direction, θ_{AS} decreases with an increase of γ across all locations. Along the long spans of the gymnasium, the values of θ_{AS} are almost constant regardless of location. In contrast, along the short spans, θ_{AS} is largest at the corners, and nearly zero at the center.

In the Y direction, the values of θ_{AS} are nearly uniform across locations, and this trend persists even as γ increases. This applies to the long spans and short spans of the gymnasium.

3.2.2 Amplification due to partially retightened anchor bolts ($0 < \gamma < 1$)

A comparison of the maximum rotation angle during the main shock (θ_{MS}) and the aftershock (θ_{AS}) at four locations in the gymnasium is shown in Fig. 10. The vertical axis represents the ratio $\theta_{AS} / \theta_{MS}$, while the horizontal axis shows the amount of repair, γ. In the figure, the aftershock coefficient β is indicated by markers. Figs. 10(a)–(d) present the X direction, while Figs. 10(e)–(h) present the Y direction. The red dotted line corresponds to $\theta_{AS} / \theta_{MS} = 1.0$. Values of $\theta_{AS} / \theta_{MS}$ greater than 1.0 indicate amplification of the column base deformation during the aftershock.



(a) Kobe, X direction

(b) Kobe, Y direction

Fig. 9 Maximum rotational angle (θ_{AS}) vs. Amount of repair (γ). Kobe, $\beta = 0.25$

In the X direction, for values of $\beta \leq 0.75$, $\theta_{AS} / \theta_{MS}$ is always smaller than 1.0 and decreases with an increase of γ. These results are consistent with the behavior shown in Fig. 9(a). However, for values of $\beta = 1.0$, $\theta_{AS} / \theta_{MS}$ exceeds 1.0 when $\gamma < 1.0$. This indicates that a repair with partially retightened anchor bolts can amplify the rotational angle during strong aftershocks.

In the Y direction, for all values of β, $\theta_{AS} / \theta_{MS}$ is always smaller than 1.0 and remains nearly unchanged with an increase of γ. These results are consistent with the behavior shown in Fig. 9(b).

Finally, the results for all earthquakes are summarized in Fig. 11. The vertical axis shows the ratio $\theta_{AS} / \theta_{MS}$, while the horizontal axis shows the aftershock coefficient, β. Figure 11(a) presents the X direction, and Fig. 11(b) presents the Y direction. Markers indicate the type of ground motion, and the red dotted line corresponds to $\theta_{AS} / \theta_{MS} = 1.0$.

In the Y direction, almost no amplification occurs for any value of β. On the other hand, in the X direction, amplification is observed at values of $\beta \geq 0.5$. Therefore, repair with partially retightened anchor bolts is effective only when aftershocks are equal or smaller than 25% of the main shock. If larger aftershocks are expected, or when design requirements demand consideration of stronger aftershocks, the maximum residual deformation δ_{max} should be fully retightened.

This study did not account for construction errors in the calculation of γ. As indicated by Fig. 10, for aftershocks with $\beta \leq 0.75$, repair ratios of $\gamma \geq 0.8$ produced responses similar to those of a fully repaired column base. Therefore, construction errors are not expected to significantly alter the seismic response in cases where full retightening is performed.

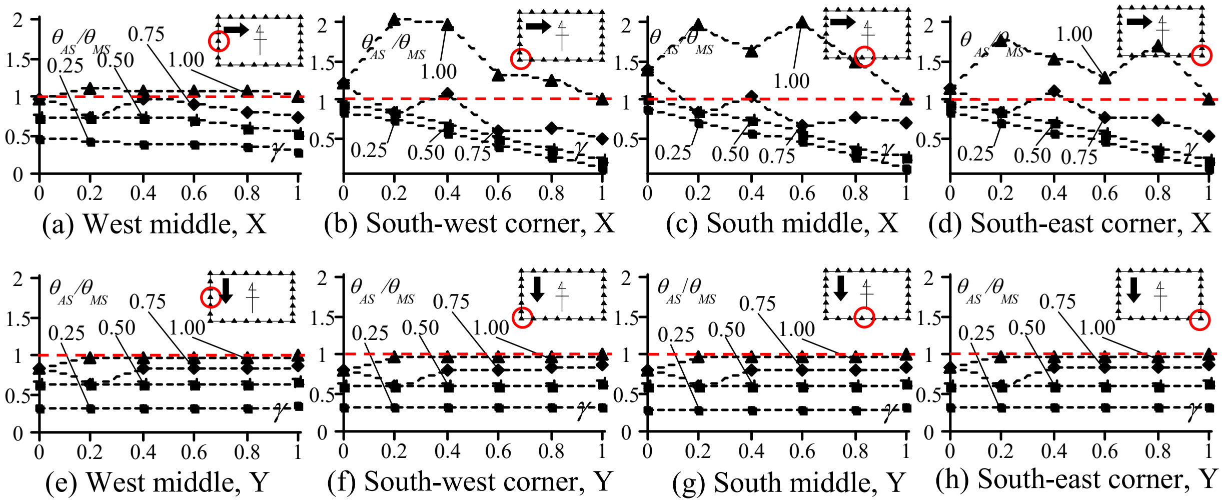


Fig. 10 $\theta_{AS} / \theta_{MS}$ Ratio vs. Amount of repair (γ), for all values of β. El Centro earthquake

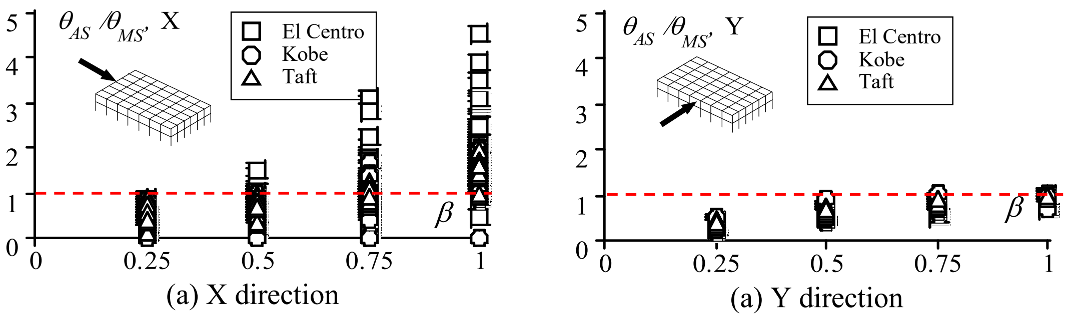


Fig. 11 $\theta_{AS} / \theta_{MS}$ Ratio for all values of β. El Centro, Kobe and Taft earthquakes

4. BALANCE OF REPAIR

4.1 Analysis method for balance of repair

The previous chapter examined the effect of the amount of repair on exposed column bases and indicated that, when repairs are carried out, the column bases should ideally be fully retightened. However, even in symmetrical buildings, an uneven distribution of repair can unintentionally amplify wall deformations. Therefore, this chapter investigates the balance of repair of exposed column bases, using the wall angle R as the primary analysis variable.

First, the definitions and parameters are introduced. In this section, retightened column bases are represented by γ = 1.0 (Fig. 3). On the other hand, the untightened column bases (γ = 0.0) are modeled using the hysteresis behavior shown in Fig. 12.

Next, the patterns of balance of repair are described. Nine patterns were considered in this study, categorized into three groups: Patterns A, with four symmetrical retightened column bases; Patterns B, with twelve symmetrical retightened column bases; and Patterns C, with six retightened column bases, arranged either asymmetrically (C1, C2) or diagonally (C3). Within each group, retightening locations varied as follows: Patterns A1, B1, C1 are retightened along the short span of the gymnasium. Patterns A2, B2, C2 are retightened along the long span of the gymnasium. Lastly, Patterns A3, B3, C3 are retightened along the corners. These nine patterns are shown in Fig. 13. In the figure, untightened column bases are shown in white, while those retightened are shown in black.

Finally, the analysis procedure is described. A time-history analysis of the main shock was first performed in the gymnasium with all column bases following the model in Fig. 3. Afterwards, each column base model was adjusted according to the repair pattern as follows: Retightened column bases adopted the model from Fig. 3, while untightened column bases adopted the model from Fig. 12. Afterwards, the time-history analysis of the aftershock was performed, obtaining values of θ_{AS} for retightened column bases and $\theta_{AS,\,ur}$ for untightened column bases. These results were used to calculate the out-of-plane wall angle (R_j) and in-plane wall angle (R_i) for each wall in the gymnasium.

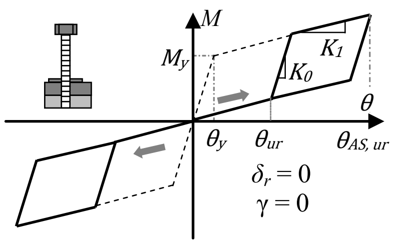
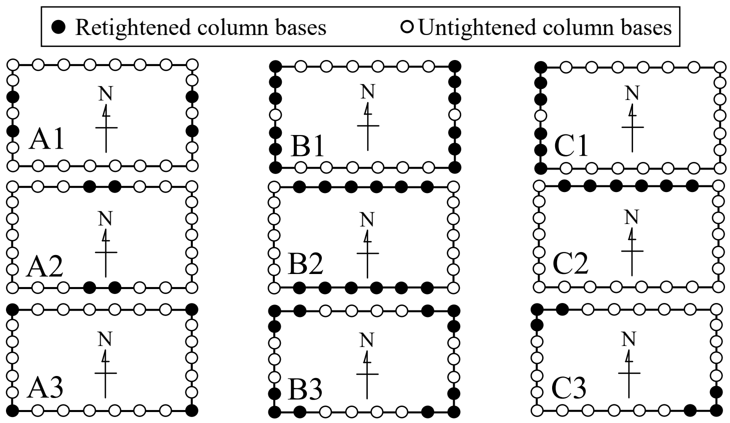


Fig. 12 Untightened model



(a) Patterns A, N = 4 (b) Patterns B, N = 12 (c) Patterns C, N = 6

Fig. 13 Patterns used for the balance of repair study

4.2 Results

4.2.1 Amplification due to balance of repair, out-of-plane

First, the out-of-plane deformation of the walls was examined. The ratio between the wall angle obtained from each repair pattern (R_j), and the wall angle obtained from an unrepaired gymnasium ($R_{no\text{-}rep}$, where γ = 0.0 for all column bases) is shown in Fig. 14. Results are based on the Kobe earthquake with an aftershock coefficient of β = 0.50. In the figure, untightened column bases are shown in white, while retightened column bases are shown in black. The dotted line in the figure indicates $R_j / R_{no\text{-}rep}$ = 1. A ratio of $R_j / R_{no\text{-}rep}$ greater than 1 represents amplification caused by the repair pattern relative to the unrepaired gymnasium.

First, the long spans and short spans were compared. In the long span, $R_j / R_{no\text{-}rep}$ = 1.0 at most locations for all patterns. However, localized amplification ($R_j / R_{no\text{-}rep}$ > 1.0) was observed, for example on the north side in Patterns A2 and C2, and on the south side in Patterns A3, C1 and C2. On the other hand, in the short span, $R_j / R_{no\text{-}rep}$ = 1.0 was observed consistently across nearly all locations and patterns. This behavior aligns with the results in Fig. 9: Fully retightened anchor bolts do not significantly affect θ_{AS} out-of-plane. This is believed to be caused by the lack of interior columns and beams that restrict out-of-plane deformation. Retightening of anchor bolts doesn't resolve this lack of support.

Next, the effect of the number of retightened column bases was examined. Comparing Patterns A (four retightened bases) with Patterns B (twelve retightened column bases), no change of R_j / $R_{no\text{-}rep}$ was observed. Thus, the number of repaired column bases has no influence in the out-of-plane wall angles.

Finally, the effect of balance of repair was considered. Comparisons between A1 and A2, as well as B1 and B2, showed similar results. On the other hand, pattern C1 produced only a small increase on the south side, while Pattern C2 showed larger increases in both the north and south sides. This is thought to be explained by the difference in length of the long and short spans, and the lack of interior frames that restrict out-of-plane deformation. Therefore, asymmetrical repair on the longer side will increase values of R more than on the shorter side, causing amplification of wall angles.

In summary, the balance of repair showed no reduction or amplification on the out-of-plane deformation of the walls in the gymnasium, as long as the repair was done symmetrically.

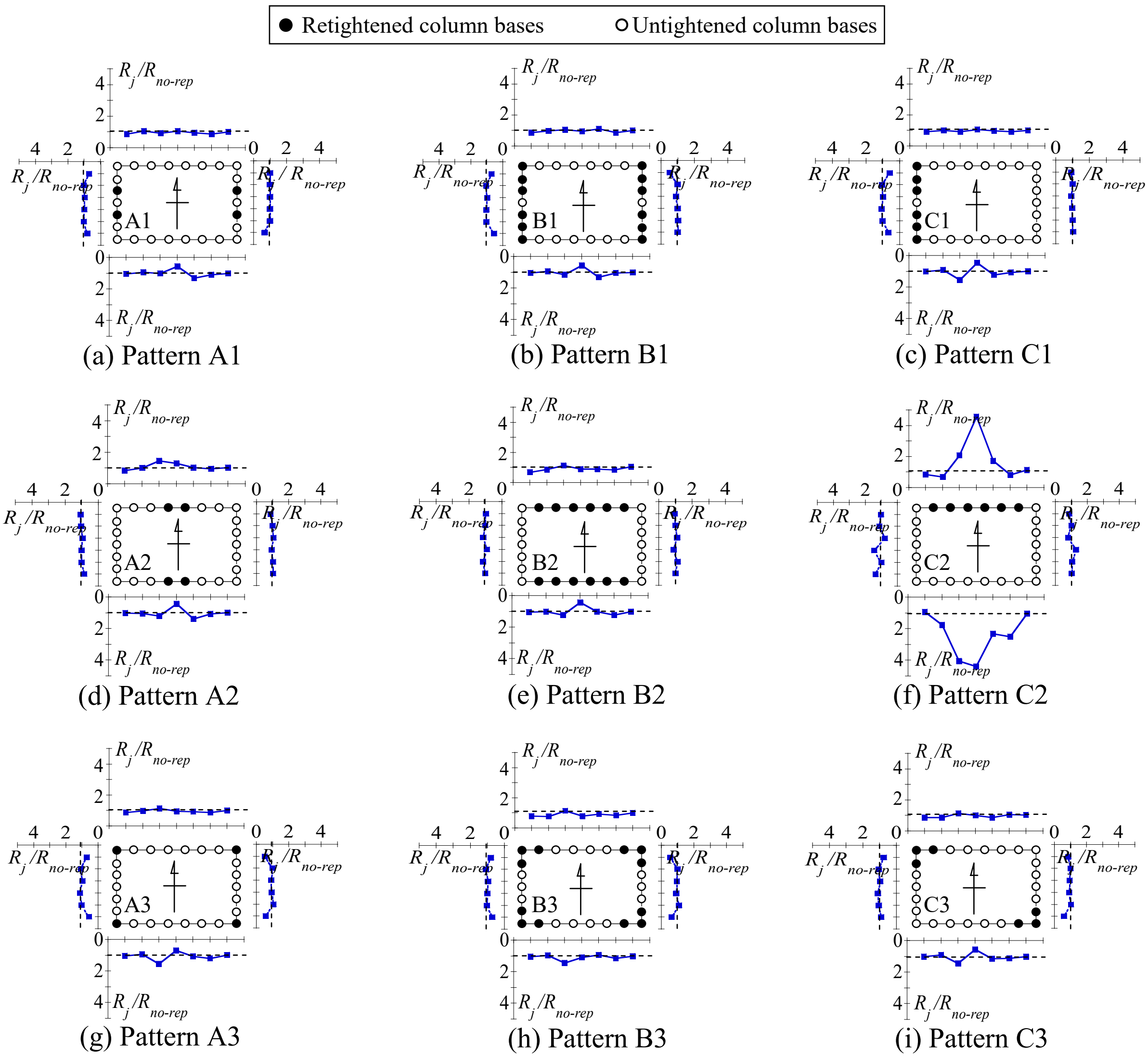


Fig. 14 Maximum values of $R_j/R_{no\text{-}rep}$ for all patterns, Kobe earthquake, $\beta = 0.50$

4.2.2 Amplification due to balance of repair, in-plane

Afterwards, the in-plane deformation of the walls was examined. The ratio R_i / $R_{no\text{-}rep}$ is shown in Fig. 15. The notation and legend of the figure is the same as Fig. 14.

First, the long spans and short spans were compared. In the long span, walls with R_i / $R_{no\text{-}rep}$ greater than 1.0 were observed in every repair pattern. For most patterns, they were observed in the north and south side. On the other hand, in the short span, the ratio R_i / $R_{no\text{-}rep}$ remained equal to 1.0 in most locations for all patterns. This behavior aligns with the behavior shown in Fig. 9: for in-plane short spans, fully retightened anchor bolts do not significantly affect θ_{AS}. Conversely, for in-plane long spans, full retightening (γ = 1.0) substantially reduced θ_{AS}.

Next, the effect of the number of retightened column bases was examined. Comparing Patterns A (four retightened column bases) with Patterns B (twelve retightened column bases), no change of R_i / $R_{no\text{-}rep}$ was observed. Thus, the number of repaired column bases has no influence in the in-plane wall angles.

Finally, the effect of balance of repair was considered. Comparisons between A1 and A2, as well as B1 and B2, showed similar results. On the other hand, Pattern C1 and C2 exhibited asymmetric distributions of R_i / $R_{no\text{-}rep}$, which reflected the asymmetry of the repair pattern itself. Nevertheless, the overall values between C1 and C2 were comparable.

In summary, the balance of repair showed amplification of the in-plane deformation of walls in the long spans, while in the short spans, the balance of repair showed no reduction or amplification.

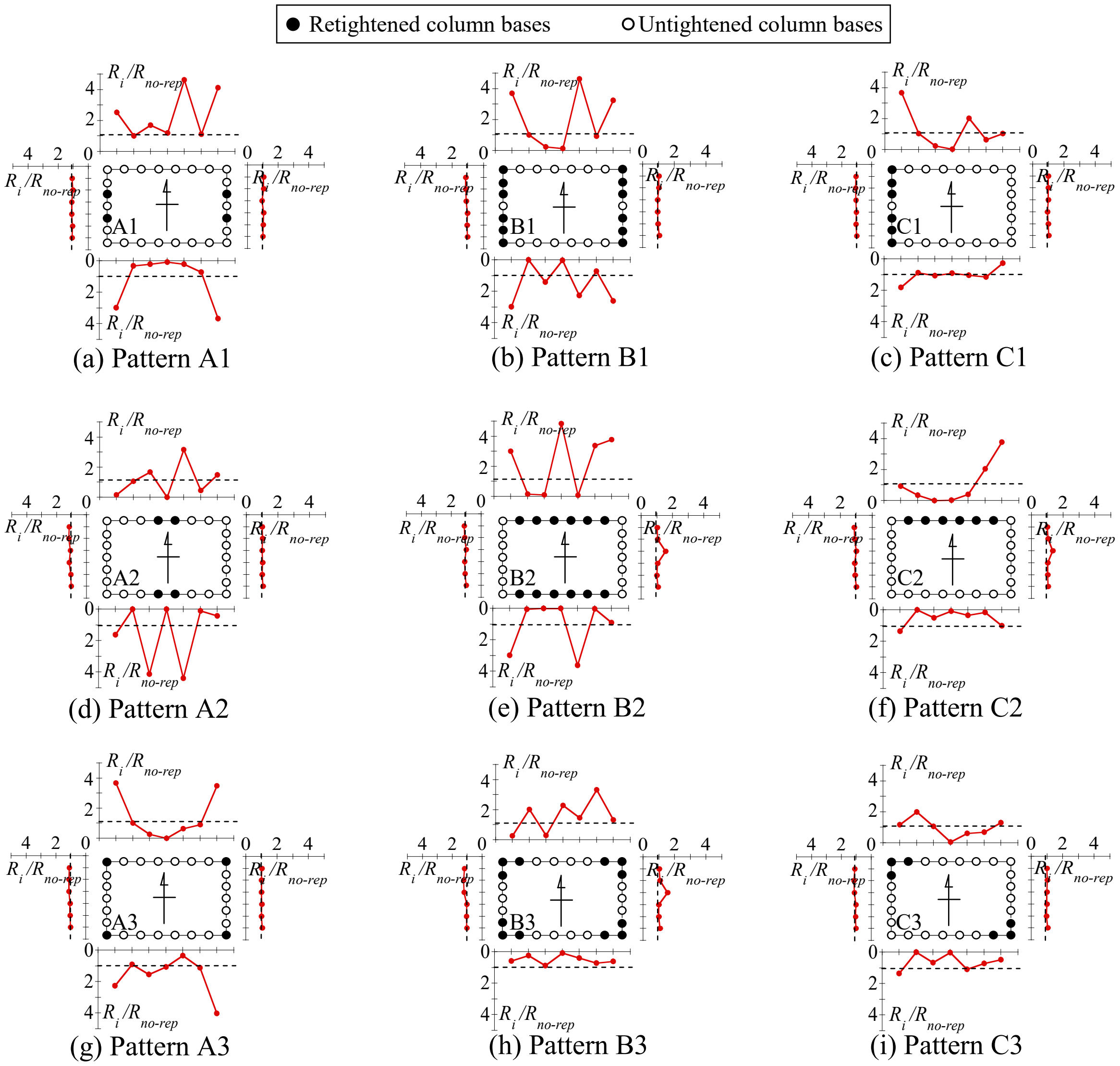


Fig. 15 Maximum values of $R_i/R_{no\text{-}rep}$ for all patterns, Kobe earthquake, β = 0.50

5. CONCLUSIONS

This study examined the detrimental effects caused by the amount and balance of repair of exposed column bases in a school gymnasium. Different combinations of main shocks, aftershocks, amounts of repair, and repair patterns were analyzed, and the results were compared against the unrepaired condition. The findings can be summarized as follows:

[1] The repair of exposed column bases using partially retightened anchor bolts ($\gamma < 1.0$) was found to be effective in the X direction, but only when the aftershock intensity did not exceed 25% of the main shock. In the Y direction, however, this type of repair showed no measurable reduction of deformation for the gymnasium considered in this study.

[2] The repair of exposed column bases using an unbalanced distribution of retightened column bases showed no reduction or amplification of the out-of-plane deformation of the walls.

[3] The repair of exposed column bases using an unbalanced distribution of retightened column bases showed no reduction or amplification of the in-plane deformation of the walls in the short span of the gymnasium. In contrast, an amplification of in-plane deformation was identified in the long span, demonstrating that an unbalanced repair pattern can have detrimental effects.

[4] Among all cases considered, none of the repair patterns avoided amplification of deformation in every wall, direction and ground motion. Furthermore, no repair pattern reduced deformations. On this basis, the study concludes that when seismic repair of exposed column bases is performed through anchor bolt retightening, all column bases should ideally be fully retightened.

[5] In actual buildings, full retightening may not be feasible due to damage to threads, nuts, or base plates, or exposed column bases might be inaccessible in a natural disaster. Nevertheless, a minimum repair ratio of $\gamma = 0.8$ should be considered when full retightening cannot be achieved, considering that repair ratios of $\gamma \geq 0.8$ produced responses similar to those of a fully repaired column base. Furthermore, since most aftershocks have a value of $\beta < 0.2$[17)], it can be said that $\gamma = 0.8$ is sufficient for most situations.

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REFERENCES

1) Ministry of Education, Culture, Sports, Science and Technology (MEXT): *Case Studies on Disaster Prevention Functions of School Facilities Serving as Evacuation Shelters*, Tokyo, Japan, 2020. https://www.mext.go.jp/a_menu/shisetu/shuppan/mext_00484.html (in Japanese, title translated by the authors, last accessed on October 10, 2025)
2) Ministry of Education, Culture, Sports, Science and Technology (MEXT): *Survey on the Disaster Prevention Capabilities of Public School Facilities Used as Evacuation Shelters, Report of Results*, Tokyo, Japan, 2023. https://www.mext.go.jp/content/20230712-mxt_bousai-000030611_1.pdf (in Japanese, title translated by the authors, last accessed on October 10, 2025)
3) Ministry of Education, Culture, Sports, Science and Technology (MEXT): *Survey on the Response of Schools and Other Institutions to the Great East Japan Earthquake, Report of Results*, Tokyo, Japan, 2012. https://www.mext.go.jp/a_menu/kenko/anzen/1323511.htm (in Japanese, title translated by the authors, last accessed on October 10, 2025)
4) Ministry of Education, Culture, Sports, Science and Technology (MEXT): *Manual for Seismic Reinforcement of School Facilities (for Structural Steel Framed Gymnasiums)*, Tokyo, Japan, 2003. https://www.daiichihoki.co.jp/store/products/detail/100314.html (in Japanese, title translated by the authors, last accessed on October 10, 2025)
5) Architectural Institute of Japan: *AIJ Design and Fabrication Guide for Steel Column Bases*, Maruzen, Tokyo, Japan, 2017 (In Japanese).
6) American Concrete Institute: *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*, Farmington Hills, MI, USA, 2008.

7) Tanaka, A., Masuda, H. and Motoda, T.: Experimental Study on the Exposed Column Bases Using Anchor Bolts with Upset Threaded Parts, *Journal of Steel Construction,* Vol. 6, No. 24, pp. 103–109, 1999 (in Japanese).
8) Baba, M., Mori, T. and Saitoh, K.: Experiment of Anchor Bolt Repaired by Tightening Nut, *AIJ Conference, Academic Lecture Abstracts, Tokai Branch,* Vol. 2012, pp. 1115–1116, 2012 (in Japanese).
9) Nakada, S. and Kishiki, S.: Effect of Paint and Rust on the Workability for Retightening Anchor Bolts, *AIJ Journal of Technology and Design*, Vol. 29, No. 72, pp. 795–799, 2023 (in Japanese).
10) Lin, K., Kurata, M., Pettinga, D., Suzuki, Y., Matsuo, S., Perea, T. and Ito, M.: Effectiveness of Repairing Anchor Rods in Exposed Column Bases in Steel Structures, *Earthquake Engineering & Structural Dynamics*, Vol. 2024, No. 53, pp. 1656–1675, 2024. https://doi.org/10.1002/eqe.4087
11) Architectural Institute of Japan (Steel Committee, Kinki branch): *Reconnaissance Report on Damage to Steel Building Structures Observed from the 1995 Hyogoken-Nanbu (Hanshin/Awaji) Earthquake*, Osaka, Japan, 2013 https://news-sv.aij.or.jp/kinki/activity/research/s_struct/tekkotu-j.pdf. (in Japanese).
12) Yamada, S., Iyama, J., Kishiki, S., Shimada, Y., Minami, S., Matsumoto, Y., Ikago, K., Ikenaga, M., Koyama, T. and Asada, T.: Reconnaissance of Damaged Steel School Buildings due to the 2011 Tohoku Earthquake, *AIJ Journal of Technology and Design,* Vol. 18, No. 40, pp. 935–940, 2012 (in Japanese).
13) Kishiki, S., Matsumoto, Y., Koyama, T., Yamada, S., Asada, H. and Shimada Y.: Damage to Column Bases and Roof Joints in Steel School Buildings due to the 2011 Tohoku Earthquake, *AIJ Journal of Technology and Design,* Vol. 19, No. 42, pp. 585–590, 2013 (in Japanese).
14) Chen, A.: *Retightening the Large Anchor Bolts of Support Structures*, Minnesota Department of Transportation & Iowa State University, St. Paul, MN, United States, 2018.
15) Saito, T.: *STERA 3D Technical Manual*, Toyohashi University of Technology, Toyohashi, Japan, 2016.
16) Nakada, S. and Saito, T.: Analytical Study on Post-Disaster Repair by Retightening Anchor Bolts on Exposed Column Base Part 1. *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*, pp. 869–870, 2023 (in Japanese).
17) Nakada, S. and Kishiki, S.: Analytical Study on Seismic Repair by Retightening Turnbuckle Braces Focusing on the Necessity and the Effect of Reducing Deformation Against Aftershocks, *Journal of Structural Engineering,* Vol. 67B, pp. 589–596, 2021 (in Japanese).

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