Seismic Retrofit of Operational Buildings Using Dampers

Tolga Onal[1]*, Javier Lopez Gimenez[1], Gen Arakawa[2]

[1]*Kawakin Core-Tech Co., Ltd.*
[2]*Kawakin Techno Solution Co., Ltd.*
* *tolga@kawakinkk.co.jp*

Abstract

Recent strong earthquakes around the world have demonstrated the vulnerability to seismic damage of structures designed using outdated seismic codes. Collapse or important damage of such structures is a major concern, since it can involve dramatic life loss and economic losses.

In Japan, energy dissipation systems, i.e. dampers, have been installed in a large number of buildings, including schools, government buildings, industrial buildings, or office buildings. This design approach, known as vibration control design, makes use of dampers to dissipate most of the seismic energy transmitted to the structure in order to move damage away from the primary structural elements of the building. This solution is very convenient for the retrofit of existing buildings, since dampers could be installed at the façade without affecting the daily operation of the building.

This paper presents the characteristics, working mechanism, and modeling approach of oil dampers when installed in a structure using a toggle-brace-damper configuration. This configuration, which features a mechanical connection of braces and dampers, amplifies the displacements of the damper around two times the corresponding inter-story drift making it especially suitable for this kind of application.

In addition, the current study evaluates the effectiveness of the toggle-brace-damper system in a typical low-rise reinforced concrete building in Turkey which does not comply with the requirements of modern local seismic codes. The seismic responses of the reinforced concrete structure in its original and seismically retrofitted conditions are evaluated and compared. Two different seismic retrofit methods are considered, i.e. the installation of diagonal braces to increase the stiffness and strength of the structure, and the installation of toggle-brace-damper systems to increase the energy dissipation capacity of the building.

The conclusions of this study show that the seismic performance of the structure is greatly improved when dampers are installed in the structure. Inter-story drifts and floor acceleration show remarkable and beneficial reductions.

Keywords: Reinforced Concrete Buildings, Seismic Retrofit, Damper, Toggle-Brace Configuration.

Introduction

Collapse or important damage of buildings is a major concern, since it can involve dramatic life loss and economic losses. The conventional approach for the seismic design of structures relies on a combination of strength and deformability of the structural elements to resist seismic actions. During strong earthquakes, structures may deform beyond the elastic range and plastic hinges are formed. In other words, structural damage of the lateral force resisting system of the building is allowed to absorb seismic energy and prevent structural collapse.

In order to move damage away from the structural elements, energy dissipation systems have been applied to a large number of buildings in Japan. This design philosophy, known as vibration control design, commonly makes use of dampers to dissipate most of the seismic energy transmitted to the structure. When applied to the retrofit of existing structures, it could prevent seismic damage in the structural frame, and unlike conventional seismic retrofit methods, the seismic retrofit works could be carried out in an easy and speedy way while maintaining the facility operational.

The current study evaluates the effectiveness of the retrofit with dampers when applied to a building in Japan by presenting the analysis results and the behavior of the damping system during the Suruga Bay Earthquake (M6.5) occurred near the building. In subsequent sections, the same design approach, i.e. retrofit with dampers, is evaluated in a low-rise building in Turkey. In this case, two different retrofit methods are compared and evaluated. The first strategy is strengthening the structure by adding diagonal braces, and the second one is installing dampers to enhance the energy dissipation capacity of the building.

Response of a retrofitted building with dampers in Japan in a recent earthquake

Description of the building and the toggle-brace-damper configuration used for the retrofit

The building retrofitted with a toggle-brace-damper configuration is a five-story office and store building with reinforced concrete structure constructed in 1963. The total floor area is 2,568m^2. The building has nine spans in its long side direction (x-direction) and one span in its short side direction (y-direction). The structure is walled frame structure in x-direction and rigid frame structure with earthquake-resistant wall in y-direction where the natural periods are 0.472sec and 0.434sec respectively after retrofit. The concrete strength of the structure is 17.1MPa~22.5Mpa. The first-floor (ground floor) plan of the building is shown in Figure 1 and the axis diagrams for the frames B and C with the toggle-brace-damper configuration are shown in Figure 2a. The number of dampers on each floor and the amplification factors for the damper configurations are shown in Figure 2b.

The toggle-brace-damper configuration (Figure 3a) features a combination of two braces per damper. The three elements are connected together in one of their ends through a freely rotational pin, while their other end is pin-connected to a beam-column joint of the frame. This damper configuration makes use of this mechanical connection in order to obtain displacements in the damper which are larger than the story drift, aiming to improve the efficiency of the device to dissipate seismic energy. Equation of the amplification factor is shown in Figure 3b.

Twelve frames of 24 units of dampers are installed inside the building in x-direction from the first floor to the fourth floor. The reason that toggle-brace-damper configuration is adopted for the retrofit of the building is that it was necessary to reduce the intervention points as it would be in the case of a conventional retrofit with diagonal braces since the building had a historical garden where the function of the building had not to be compromised. The photos of the installed vibration control devices are shown in Figure 3c.

In the x-direction where dampers are installed, some walls around the openings have seismic slits and some columns are reinforced with carbon fiber sheet winding in order to prevent brittle fracture of the columns. In the y-direction as there were many earthquake-resistant walls, instead of adopting dampers, strength-type reinforcement is used by closing the openings of existing structural walls.

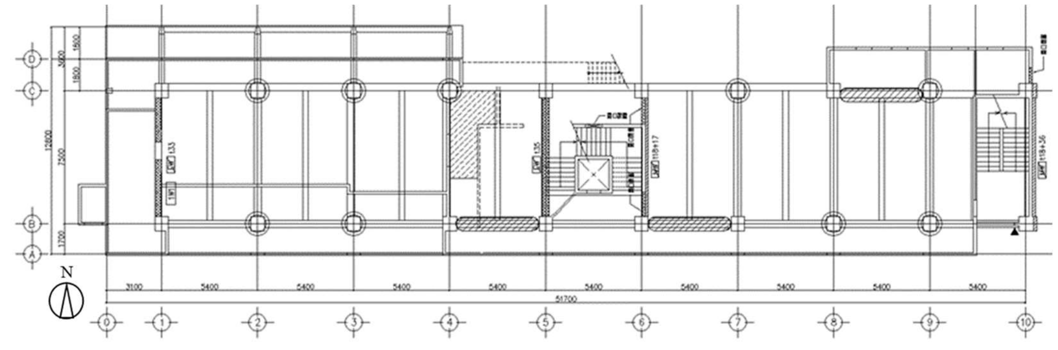
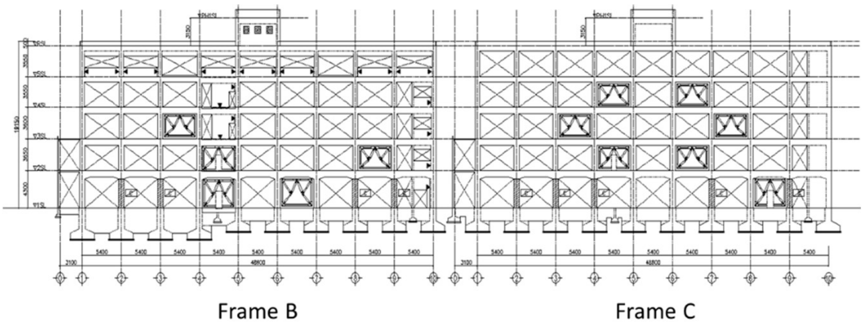


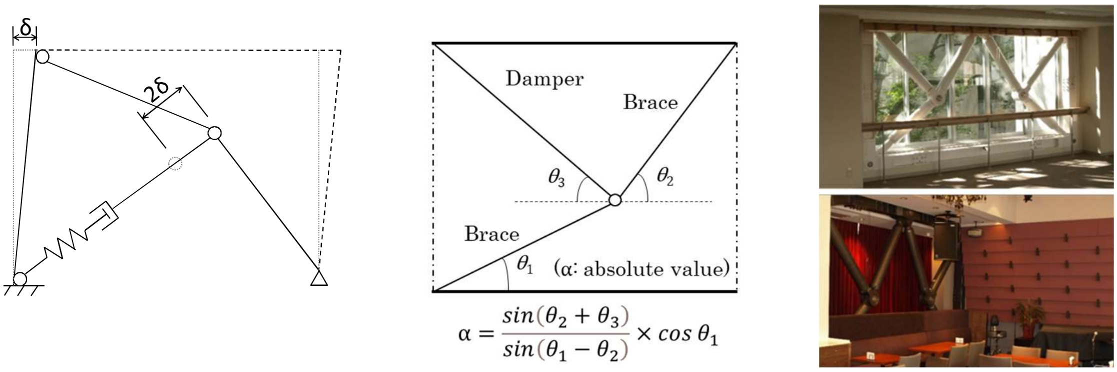
Figure 1. floor plan (ground floor)



Floor	No. Of Dampers	Amplification Factor (α)
5	0	-
4	4	2.4
3	6	2.0 , 2.4
2	8	2.0 , 2.4
1	6	2.2

a) b)

Figure 2. a) axis diagrams for the frames B and C b) amplification factors for the dampers



a) b) c)

Figure 3. a) toggle-brace-damper mechanism b) equation of amplification factor (α) c) vibration control devices installed

The dampers used for the toggle-brace-damper configuration

The dampers used are oil dampers which are hydraulic devices that dissipate seismic energy by pushing a fluid through an orifice. In this case, the flow of the fluid through the piston is controlled by relief valves installed in the orifices of the piston head. The resultant damping force is velocity dependent and follows a bilinear relationship with F_r and F_m as the release force and maximum force respectively. In this study, dampers are modeled using the Maxwell model. It consists of a linear spring, k=120kN/mm, in series with a bi-linear dash pot element with the parameters described in Figure 4a. The validity of the performance of this damping system has been confirmed by public institutions (Figure 4b) (Arakawa and Shinbayashi, 2005). The force and displacement relationship of the damper as well as the actuator is shown in Figure 4c.

a) b) c)

Figure 4. a) relationship of damping force and velocity b) dynamic loading test c) damping force and displacement relationship of the damper

The design criteria for the retrofit are shown in Table 1. The criteria are based on the standard for seismic evaluation proposed by the Japan Building Disaster Prevention Association.

Table 1. Design criteria for the retrofit

1	Shear failure to be prevented in vertical members
2	The axial force of the vertical members to be below the limits (1F~5F: 0.37×Ac×σB, B1F: 0.40×Ac×σB) (Ac: Column cross section, σB: Actual strength of the concrete)
3	Maximum interlayer deformation angle to be less than 0.67% (1/150)
4	The damping force, velocity and the deformation of the dampers to be within limits (damping force: 550kN, velocity: 62.5cm/sec, deformation: ±110mm)

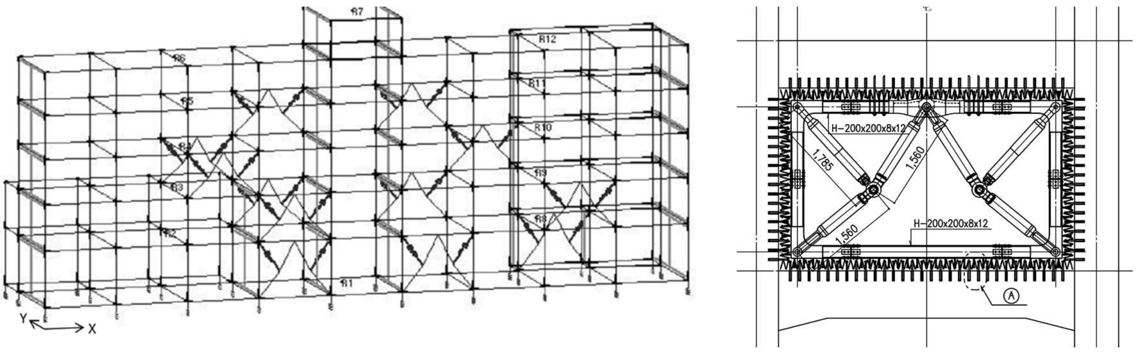
For the input seismic ground motion, the records and the waves indicated in Table 2 are used.

Table 2. Input seismic ground motions

1	Observed strong earthquake records (Maximum velocity standardized to 50cm/s)	El Centro 1940 NS
2		Hachinohe 1968 NS
3		Taft 1952 EW
4	Simulated wave of safety limit proposed by The Building Center of Japan	BCJ_L2, Original Wave
5	5 waves are stipulated in building standard law in Japan (KOKUJI Wave), return period of 500 years. It was observed from the boring data of the building site that engineering bedrock which shear wave velocity is 400m/s or greater existed at a depth of 14.6m. Waves at the engineering bedrock are fitted to the spectrum amplifying by the seismic hazard zoning factor Z(=1.2). KOKUJI Wave was computed using SHAKE, an equivalent linear analysis software, based on the ground information of the site considering the engineering bedrock and the soil model for clay or sandy soil.	KOKU_R1, Random Phase angle
6		KOKU_R2, Random Phase angle
7		KOKU_R3, Random Phase angle
8		KOKU_EL, El Centro NS Phase angle
9		KOKU_HAC, Hachinohe NS Phase angle

Adopting dampers in a toggle-brace configuration in the x-direction, time history response analysis confirmed that the inter-story drifts could be reduced below 0.67% (1/150), which was the design criterion. In addition, non-linear static (pushover) analysis confirmed that no shear failure occurred in vertical members (columns) up to an inter-story drift of 0.80% (1/125). In the y-direction where strength-type reinforcement was adopted, it was confirmed that the target value was satisfied by the second and third level diagnoses of seismic assessment methodology proposed by the Japan Building Disaster Prevention Association. The analysis model of the building is shown in Figure 5a.

The installation method is shown in Figure 5b. The inner frame in which the dampers are installed is made of steel, and connected to the structure by a series of chemical anchors uniformly distributed along the RC structure, shear studs on the steel frame, and steel spirals. The space between frame and building is filled with high strength mortar to ensure the appropriate transfer of loads between both structures. In building models, the steel frames were not included in the model, and the braces and dampers were modeled as if they were directly attached to the existing structure. Special attention was paid to the design of the connections between the existing structure and the inner frame where the toggle-brace-dampers are installed. The method was designed by multiplying the anchor strength by a reduction factor. The responses before and after the retrofit are shown in Figure 6.



a) b)

Figure 5. a) 3D analysis model of the building b) installation method

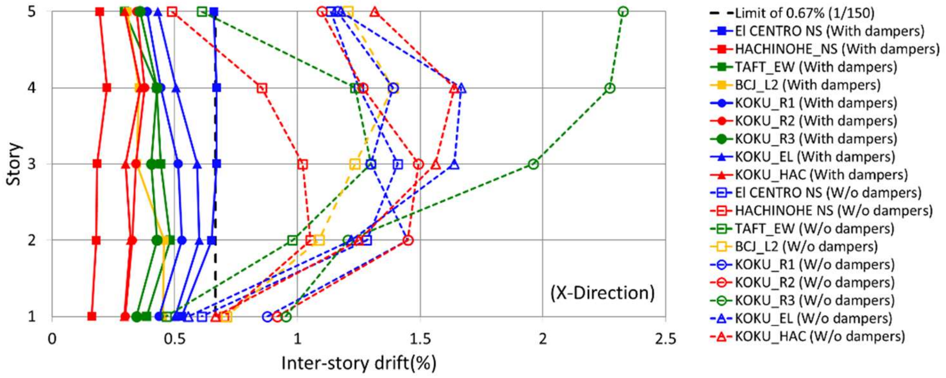
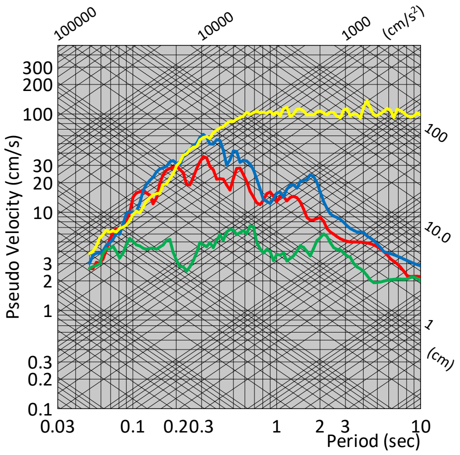


Figure 6. response graph before and after the retrofit

Investigation and verification after the Suruga Bay Earthquake

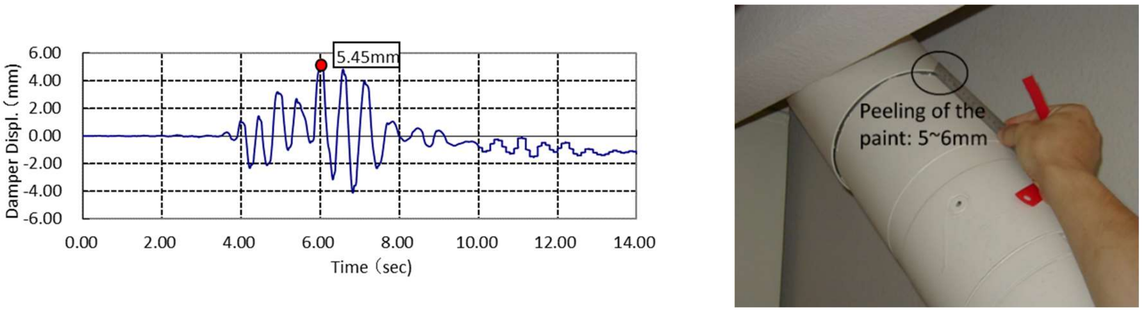
Seismic intensity of "5-" based on the JMA (Japanese Meteorological Agency) Scale was observed near the building during the Suruga Bay Earthquake (M6.5) on August 11, 2009. The amount of damper displacement observed during the survey after the earthquake coincided with the results of the non-linear time history analysis performed using the ground motion recorded near the building (record of “SZ0014”, Shizuoka Prefectural Office, released by K-NET). The tripartite response spectra, with 5% damping, of the strong motion records are shown in Figure 7. There was no damage due to the earthquake.



Line Type	Seismic Wave
🟥	Recorded Wave SZ0014 (Shizuoka) _EW in x-direction (maximum acceleration: 300.96cm/s^2
🟦	Recorded Wave SZ0014 (Shizuoka) _NS in y-direction (maximum acceleration: 308.40cm/s^2)
🟩	Recorded Wave SZ0014 (Shizuoka) _UD in vertical direction (maximum acceleration: 132.15cm/s^2)
🟨	Officially Designated Wave for Design (KOKUJI Wave)

Figure 7. tripartite response spectra (5% damping)

During the investigation performed after the earthquake, on the 2nd floor it was observed that the peeling part on the paint of a damper was 5 to 6mm which was an indicator of its displacement. The observed displacements match the analysis result (Figure 8).



a) b)

Figure 8. displacement of the damper on the 2nd floor a) analysis result b) photo of the moving part

Building in Turkey studied for retrofit

Description of the building

The building object of study is a two-story office building. The total height is around 8.4m, with standard floor heights of 4.2m. The maximum cross-sectional dimensions of the columns are 300mm × 600mm and the standard distance between adjacent columns is 4500mm in long side direction (x-direction) and 8000mm in short side direction (y-direction). It is a reinforced concrete moment resisting frame system designed before the introduction of modern and more severe seismic design codes.

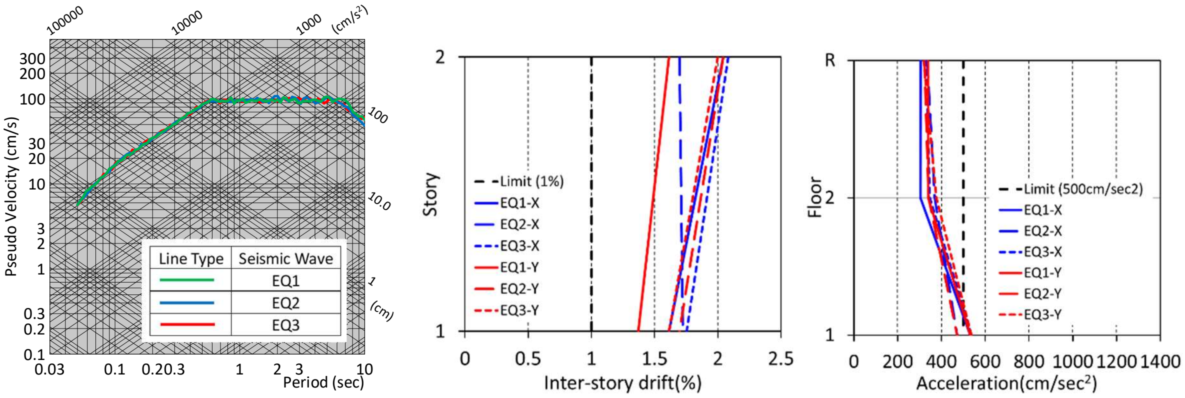
Dynamic analysis of the structure

A three-dimensional model of the building described above was developed and analysed using SNAP Ver.7, a Japanese commercial software for seismic response analysis.

The columns and beams of the structure are included in the model as nonlinear elements. Beams are modelled using moment springs at the ends and shear springs at the center of the beams. The model of the columns includes multi-spring models at both ends and shear springs at the center point. The hysteresis rule for the moment springs of the beams is based on the model by Takeda, while the origin-oriented hysteresis model is adopted for the shear springs of the columns and beams. Concrete strength is 18MPa and steel strength is equal to 220MPa. Structural damping is modelled by stiffness proportional damping, in which the first mode damping factor in x-direction is set to 0.03.

The structural model is excited with a total of 3 ground motion time histories. These are artificially generated with random phase angles uniformly distributed, and have been matched to the design spectra described in the Turkish Seismic Code (2018). The obtained ground motion time histories are input in the model along the x-direction and y-direction separately. The tripartite response spectra, with 5% damping, of the input time history earthquake records are shown in Figure 9a.

Nonlinear time history analyses were carried out subjecting the structural model to the different earthquake ground motion records described above. The response of the building was evaluated in terms of maximum inter-story drifts and maximum horizontal accelerations. Figure 9b presents the maximum inter-story drifts in x and y directions when the building is subjected to the different earthquake ground motion records. The maximum allowable value for the inter-story drift is set to 1.00%.



a) b) c)

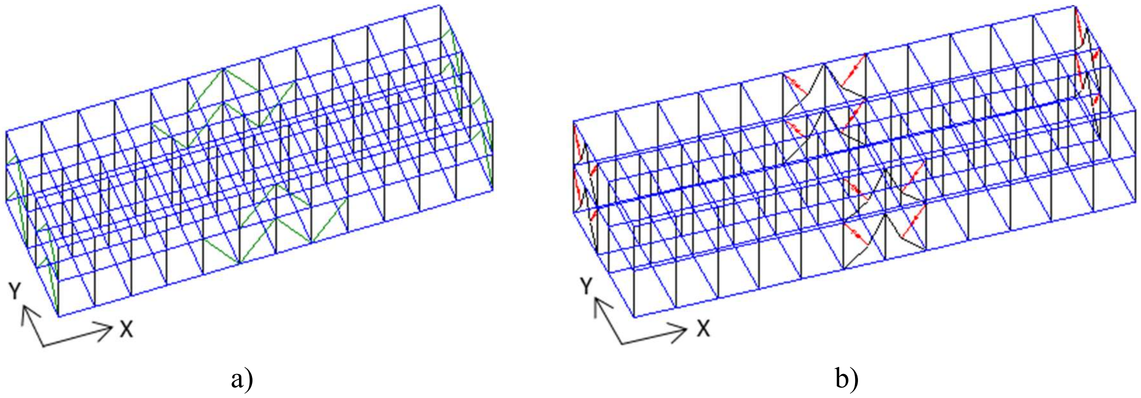
Figure 9. a) tripartite response spectra (5% damping)
b) maximum inter-story drifts c) maximum horizontal accelerations

The obtained drifts are above the proposed limit for all earthquake inputs in both directions. In the x-direction, EQ3 represents the worst-case scenario with values of 1.75% and 2.08% for the first and second stories respectively. EQ2 ground motion time history induces similar maximum drifts in the y-direction. These results represent a remarkable risk of collapse or loss of serviceability of the existing structure. The maximum horizontal accelerations induced in each floor are shown in Figure 9c. Aiming for a minor damage and small-scale repair works in the event of a strong earthquake, the maximum allowable value for the accelerations in the 2nd story and the roof level is set to 500cm/s^2 (Japan Structural Consultants Association, JSCA, 2002). Maximum accelerations are observed in the 2nd story when subjecting the structure to EQ3 seismic wave in the y-direction. The obtained value of 376.2 cm/s^2 is lower than the maximum allowable acceleration set for this study.

Seismic retrofit schemes

In order to reduce the large inter-story drifts to meet the set performance criteria, two different strategies are evaluated. Due to the nature of the considered structure, it was necessary that the proposed seismic retrofit solutions could be able to be installed in an easy and speedy way while maintaining the facility operational.

The first strategy considered in this study to reduce the excessive inter-story drifts is increasing the stiffness of the structure by installing braces in an outer steel frame connected to the façade of the building. The braces are H section wide flange steel beams with cross-sectional dimensions 200×200×8×12 mm. A total number of 28 braces are installed in the building, i.e. 12 in the x-direction and 16in the y-direction, as shown in Figure 10a.

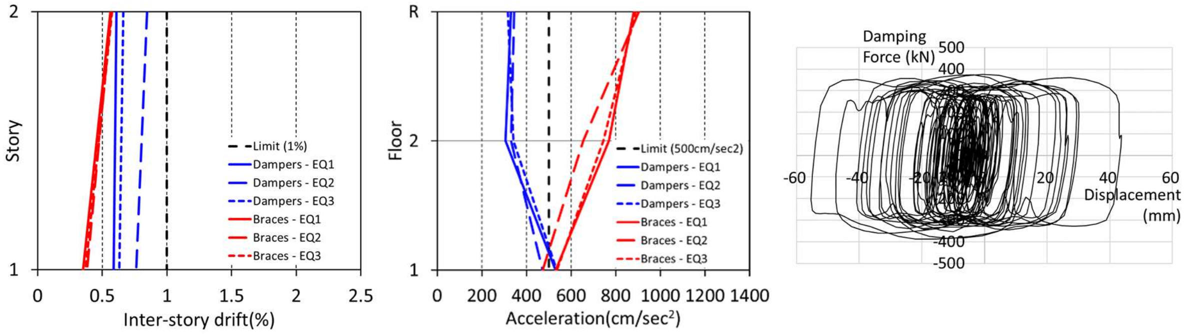


a) b)

Figure 10. a) model with braces b) model with toggle-brace-damper systems

The second approach consists of the installation of oil dampers in the structure in a toggle-brace-damper configuration. The objective is to provide an additional mean of seismic energy dissipation which can help to reduce the excessive inter-story drift observed in the original model. The dampers are modelled using the Maxwell model. It consists of a linear spring, k=137.2kN/mm, in series with a bi-linear dash pot element with the parameters C1 of 50kN/(cm/sec), C2 of 4kN/(cm/sec), F_r of 300kN and F_m of 550kN. The amplification factor for the toggle-brace-damper considered in this study is equal to 2.0. The toggle-brace-dampers are installed in a steel outer frame connected to the façade of the existing building in order to maintain the facility operational during the retrofit works. The total number of sets of dampers installed in the building is equal to 16 (Figure 10b).

The proposed schemes for seismic retrofitting are both effective in reducing the excessive inter-story drifts of the original model. The obtained analytical results show drifts which are below the limit value of 1.00% for all earthquake inputs in both directions. The results of the inter-story drifts in x-direction are presented in Figure 11a. Maximum inter-story drifts are very similar in the case of the building retrofitted with braces, regardless of the earthquake input. The model with dampers subjected to EQ3 shows larger inter-story drifts equal to 0.76% and 0.85% for the first and second stories respectively. Figure 11b shows the maximum horizontal accelerations in x-direction at the 2nd story and roof level for both retrofitted models. The force and displacement relationship of the dampers for the 1st story is shown in Figure 11c. The results reveal that retrofit with braces increase the accelerations in the structure beyond the proposed limit in all study cases, which can lead to costly repairs in the event of a future earthquake. Maximum accelerations at the roof level reach 881.9cm/s^2 in x-direction and 1140.6cm/s^2 in y-direction. On the other hand, the maximum accelerations in the building models equipped with toggle-brace-damper system beneficially remain below the proposed limits for all the analysed cases in both directions.



a) b) c)

Figure 11. a) maximum inter-story drifts in x-direction b) maximum accelerations in x-direction c) damping force and displacement relationship of dampers (1^{st} story)

Conclusions

The following conclusions can be withdrawn from the obtained results of the retrofit of buildings with toggle-brace-damper system and the results of the comparison with retrofit by adding diagonal braces:

- The observed behavior of the toggle-brace-damper system in an earthquake matches the analysis results.
- Installation of diagonal braces in the structure reduces inter-story drifts below the set performance objective, but detrimentally increases the accelerations induced to the structure.
- The building retrofitted with toggle-brace-dampers presents both low inter-story drifts and horizontal seismic accelerations.

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