International Journal of High-Rise Buildings
September 2018, Vol 7, No 3, 215-221
https://doi.org/10.21022/IJHRB.2018.7.3.215

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Design and Applications of Buckling-Restrained Braces

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Abstract

Buckling-Restrained Braces (BRBs) have been widely applied to tall buildings in seismic areas in the world. In this paper the author summarizes representative types of BRB compositions and shows two cases of special applications of BRBs. In the first case, BRB diagonals for tall building were used to provide stable cyclic nonlinear hysteresis and also used to limit forces generated at columns, connections and walls. The top outriggers are pre-loaded by jacks to resolve long-term differential shortenings between the concrete core wall and concrete-filled steel box columns. The second case is the retrofit work for a communication tower by replacing the insufficiently strong members with BRBs in Japan.

Keywords: Buckling-Restrained Braces (BRB), Damage tolerant structures, Outrigger system, Pinned connection, Reinforcement site work

1. Introduction

The Buckling-Restrained Brace (BRB) is a axial composite member that buckling restrainer provided around the core member that bears the axial force to prevent overall buckling.

The first Buckling-Restrained Braces for practical use was achieved by Watanabe et al. (1988) (Fig. 1.1) in 1988. They employed rectangular steel tubes with in-filled mortar for the restrainer and discovered the optimal coating material specifications to obtain a stable symmetry hysteresis behavior. Also they have established the basic theory of the buckling mechanism and design formulas of the restrainer. These BRBs were applied to 15-stories and 10-stories steel frame office building in 1989, which is the first Buckling-Restrained Braced Frame (BRBF) in the world (Fujimoto et al., 1990). After this application, the concept of BRBs have been gaining popularity and other types of BRBs, such as double tubed BRBs have been developed for practical use. In the 1990s, BRBs have been applied to more than 100 tall buildings in Japan, and the concept of "Damage Tolerant Structures" has been proposed by Wada et al. (1992), which treats BRBs as energy-dissipating elasto-plastic dampers preventing the damages

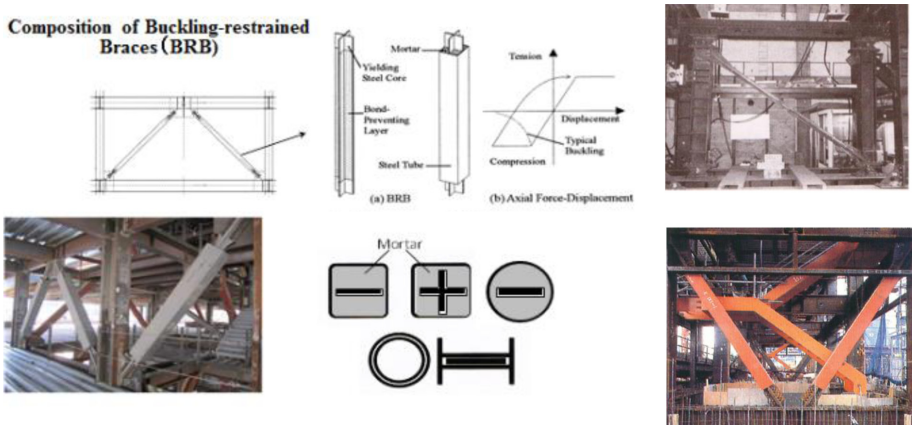


Figure 1.1. Composition of Buckling-restrained Braces (BRB) (Watanabe et al., 1988; Fujimoto et al., 1990; Wada and Takeuchi, 2017).

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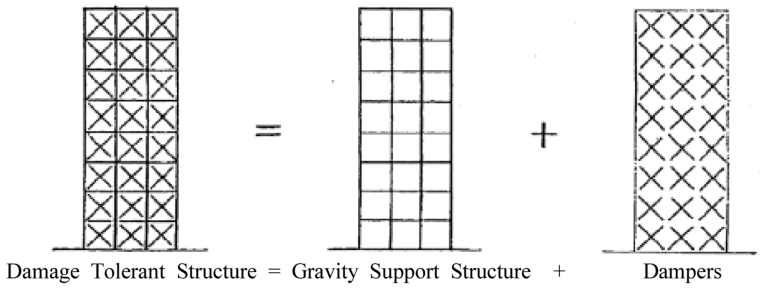


Figure 1.2. The Concept of Damage Tolerant Structure (Wada et al.).



Photo 1. The first BRB Building.

of the main frame.

In the early 2000s, applications in Taiwan have also started (Tsai et al., 2004). Ten years later, BRBs have become widely known in seismic areas in the world, and various researches are ongoing in Japan, U.S., Taiwan, China, Turkey and other countries.

2. Compositions and Material of BRB

2.1. Compositions of BRB

Representative types of BRB compositions are summarized in Fig. 2.1. The most popularly used composition is the core of plate or cross section with the rectangular or circular hollow section steel tubes with in-filling mortal in between as shown in Fig. 2.1.(a) (Wada and Takeuchi, 2017; Nippon Steel Engineering, 2018; Star Seismic, 2018). Coating materials are usually provided to disconnect the core from the mortar, giving the clearances to allow the expansion of the core sections. End connections have a variety of bolted, welded, and pin-ended. The tolerance of the clearances and overall stabilities depends on the fabrication process and the detail at the restrainer-ends.

2.2. Core Steel Material

To prevent the global buckling of the system, the maximum axial force of the core member after yielding needs to be controlled under the critical buckling forces of the restrainer. Therefore, the steel material used for the core member is desirable to have the upper limit in yield stress. The steel materials often used for BRB core is listed in Table 2.1 (Wada and Takeuchi, 2017; JIS, 2012; ASTM, 2018). Under monotonic loading, the yield strength and elongation in each steel material shows inverse proportional relationship as shown in Fig. 2.2. Low yield strength steel such as LY100 and LY225 in Japan are the materials produced for energy-dissipating elasto-plastic dampers.

3. Applications and Installation of BRB

3.1. Wilshire Grand Tower

The Wilshire Grand Center is the tallest building (335.3 m, 73-story) in Los Angeles. A lateral system consisting of a concrete core wall with outriggers and belt trusses emerged as the best option for this building, because it provided adequate lateral stiffness for wind comfort without the need for a tuned mass damper. The outrigger

Table 2.1. Steel Materials for BRB Core Member (Wada and Takeuchi, 2017; JIS, 2012; ASTM, 2018)

Steel grade	Standard	Min. yield stress (N/mm^2)	Max. yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
LY100	※LYS	80	120	200-300	50-
LY225	※LYS	205	245	300-400	40-
SN400B	JIS	235	355	400-510	21-
SN490B	JIS	325	445	490-610	21-
A36	ASTM	250	-	400-550	
A572Gr.50	ASTM	345	-	450-	21-

※ Low yield strength steel qualification certified by the Minister of land, infrastructure, transportation and tourism, Japan

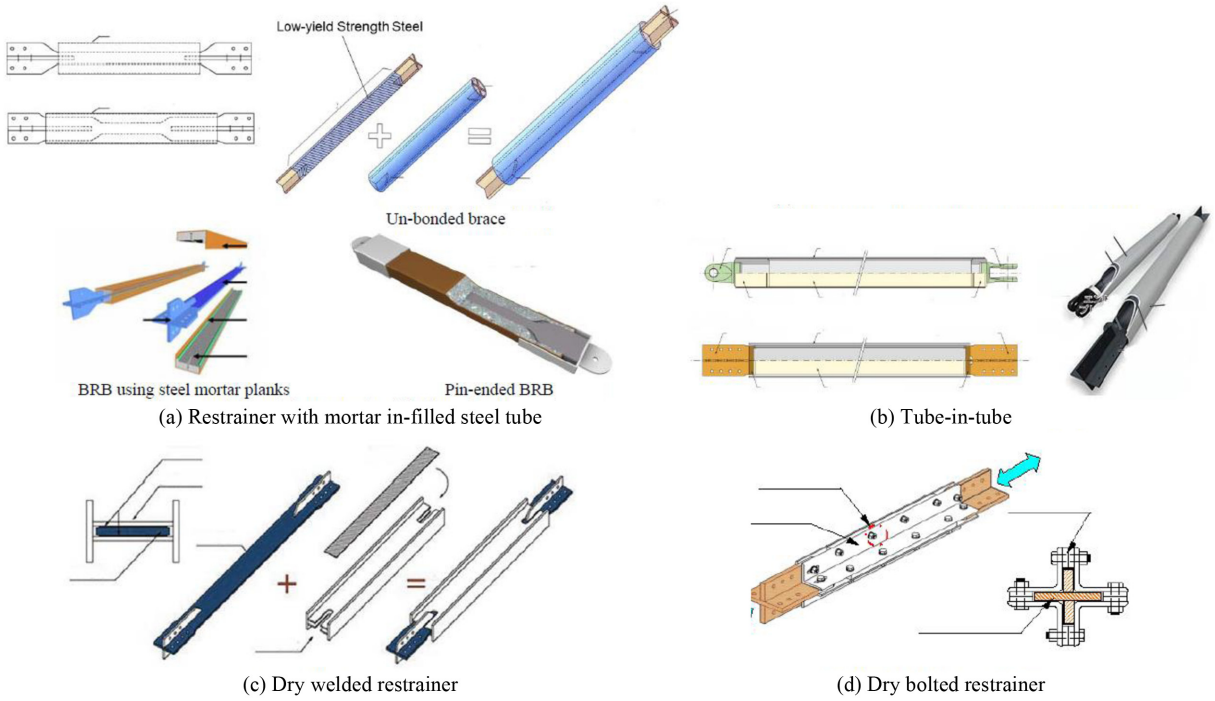


Figure 2.1. Representative types of BRB compositions (Wada and Takeuchi, 2017).

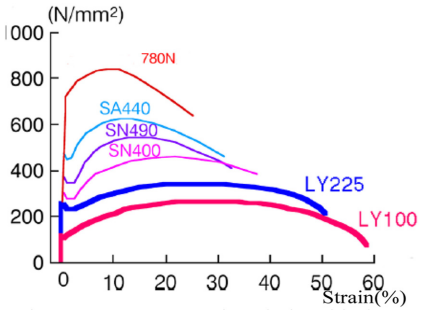


Figure 2.2. Stress-strain relationship in different strength steel materials (Wada and Takeuchi, 2017).

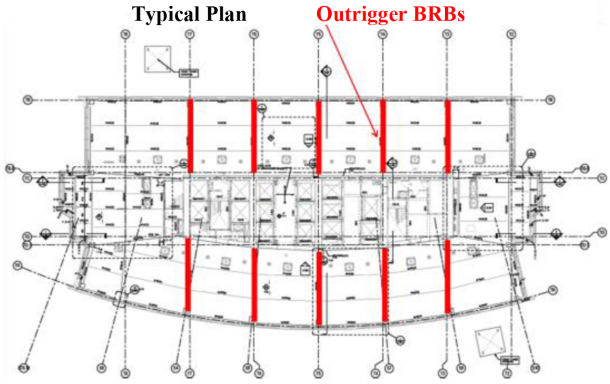


Figure 3.1. (a) Typical plan.

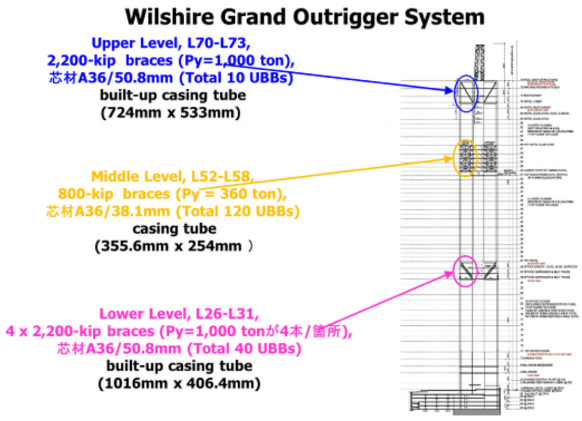


Figure 3.1. (b) Outrigger System (Joseph et al., 2016).

braces at the lower and upper levels span multiple floors. Utilizing BRBs allowed the team to design for a slender brace. In addition, BRBs provide for predictable limits on member and connection forces (STRUCTURE, 2015).

The structural designer investigated the use of conventional brace elements as part of the outrigger system. But these conventional braces were sized based on compression buckling, making them much larger than necessary for the tension forces. This caused the brace connections to be much larger, as well, and increased the tensile demands on the outrigger braces and the foundation.

Therefore, BRBs were selected so that the brace area could be sized based on tensile capacity, since BRBs have essentially the same capacity in either axial direction. This made the connections to the core wall and outrigger col-

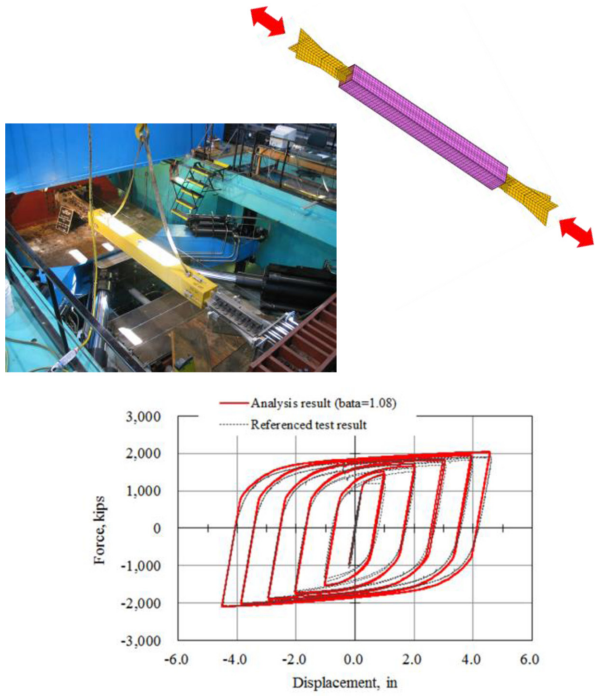


Figure 3.2. Nonlinear Finite Element Analysis of BRB.

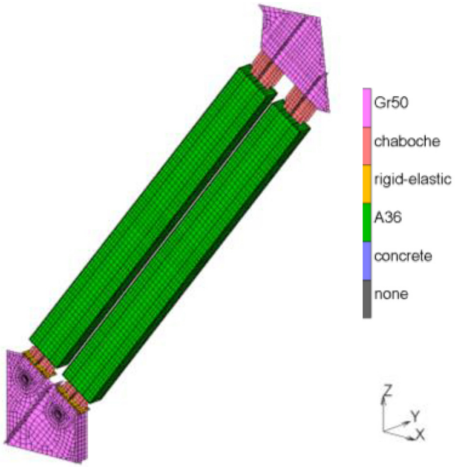


Figure 3.3. The Lower Upper Outrigger BRBs.

umns less demanding, and made the outrigger columns smaller. The BRBs serve as a fuse and limit seismic forces and provide a repeatable, predictable load to the foundation via the columns (STRUCTURE, 2015).

Nonlinear finite element analysis by applying the mixed hardening Chaboche model by which is possible to consider the Bauschinger effect under reverse loading path was conducted to compare with the referenced test result (Fig. 3.2).

The Lower Upper Outrigger BRBs are connected to the core wall with steel embed plates. Gusset plates are welded to the embed plates to receive the double-pinned connections for the "2x2" BRBs (Fig. 3.3).

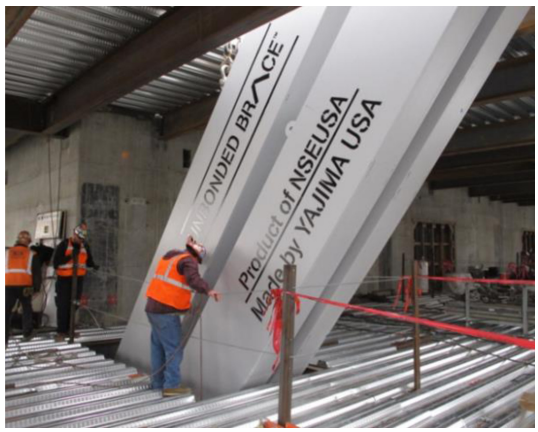


Photo 3.1. The Lower Upper Outrigger BRBs.

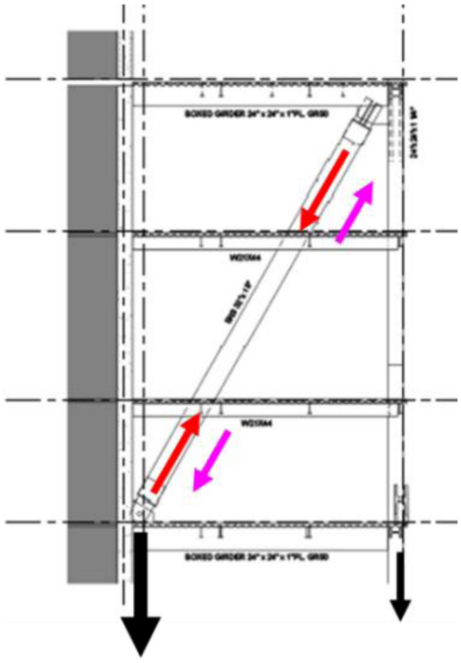


Figure 3.4. Sinking from Axis Shrinkage of the Columns.

After completion of the structure, the elastic shortening of the steel is complete except for that associated with occupant live loads. As the concrete core wall shrinks and creeps, the Upper Outrigger BRBs goes into tension. The Upper Outrigger BRBs are single 2,200-kip braces, which are sensitive to the differential movement between the shrinkage, creep and elastic shortening of the core wall and the elastic shortening of the structural steel box columns (Fig. 3.4). To mitigate the large force transfer due to differential building movements, the BRBs will be jacked with a pre-compression force to 5,000 kN. This pre-compression in the BRBs will result in a temporary tension force in the exterior box columns. Over time, as the core wall creeps and shrinks, the BRBs will transition from compre-

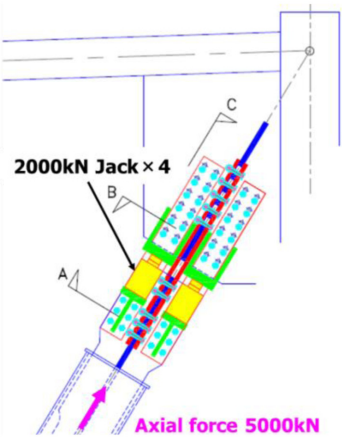


Figure 3.5. Connection of BRB Jacked with a Pre-Compression Force to 5,000 kN.



Photo 3.2. BRB Installed Axial Force by 4 Jacks.

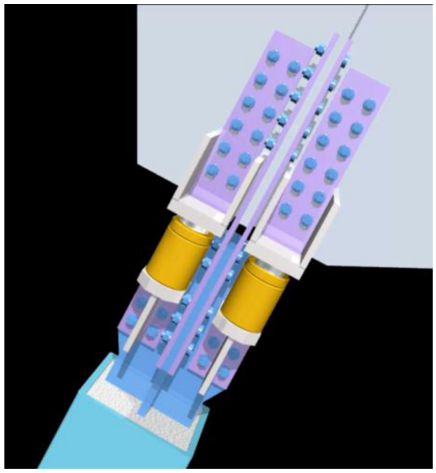


Figure 3.6. BRB Installed Axial Force by 4 Jacks.

ssion to tension, while the exterior box columns will transition from tension to compression (Figs. 3.5 ,3.6) (STRUCTURE, 2015).

The use of BRBs provided the necessary strength and stiffness in the transverse direction to provide for occupant wind comfort, drift control for wind and seismic, and strain compatibility with creep and shrinkage of the concrete core.

3.2. Retrofit work for a Communication Tower

The BRB system is also used to retrofit truss structures. Fig. 3.7 shows a communication tower constructed in Japan in the 1970s. Such towers have been constructed on the roof of buildings, and they suffer from risks of collapsing during severe earthquakes as a result of amplification by the supporting buildings.

Because such fractures are caused by partial stress concentration at critical members, the most effective retrofit method is to replace these members with stable energy-dissipation members such as BRBs, in which the plastic strain is evenly distributed along the braces.

Fig. 3.8 shows the retrofit work for a communication tower in Japan. Various retrofit options are compared in the Fig. 3.8 (Takeuchi, 2005; Takeuchi, 2013). One of these is the addition of buckling restrainers around members having insufficient increasing axial strength; the buckling restrainers prevent buckling, thus resulting in increased axial strength (center of Fig. 3.8). This enhances the structure's seismic response, but requires additional reinforcement around the 50-year period interval earthquake. The other option is to replace the insufficiently strong members with BRBs (right side of Fig. 3.8). The analyzed acceleration responses of each of the options are shown in Fig. 3.9. The option involving replacement with BRBs has the minimum response acceleration throughout the height, higher performance, and the lowest construction cost. Consequently, this option was selected and applied to 50 towers in Japan. Retrofitting of 20 BRB members could be completed in just six days with three workers, thus proving to be one of the most practical and cost-effective retrofit methods (Photo 3.3).

4. Conclusion

Using BRBs as outriggers between RC core wall and steel frames is becoming common, because BRBs support "Damage Tolerant Structures" which treats BRBs as energy-dissipating elasto-plastic dampers preventing the damages of the main frame. Also, using BRBs makes Performance Based Seismic Design (PBSD) Process simple by Nonlinear Response History Analysis (NRHA) and provide for predictable limits on member and connection forces. BRBs will be used more widely to reduce the damage of the building by an earthquake.

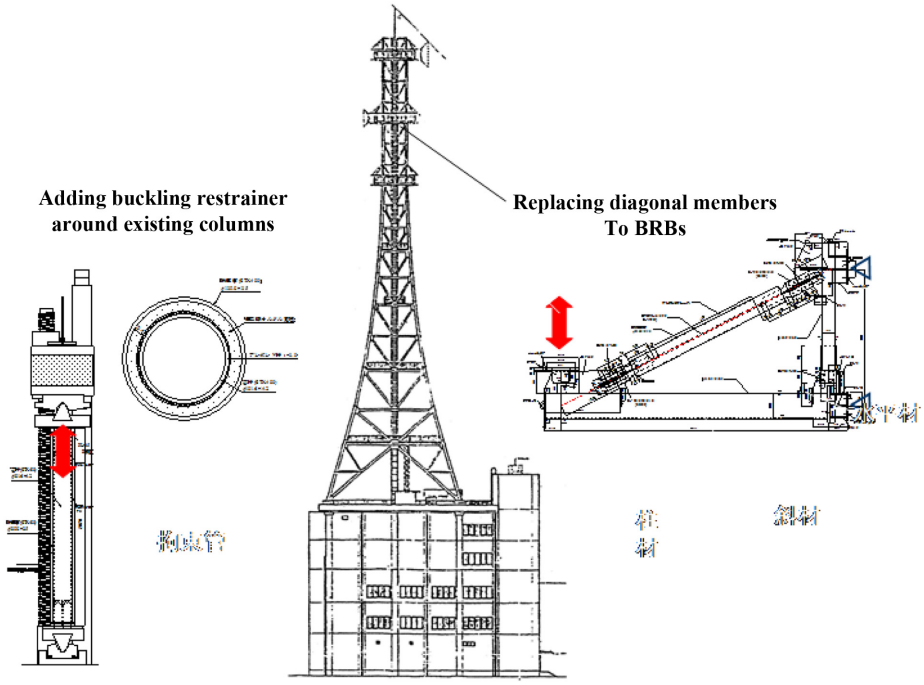


Figure 3.7. Seismic Retrofit of Tower Structures with BRBs (Wada and Takeuchi, 2017).

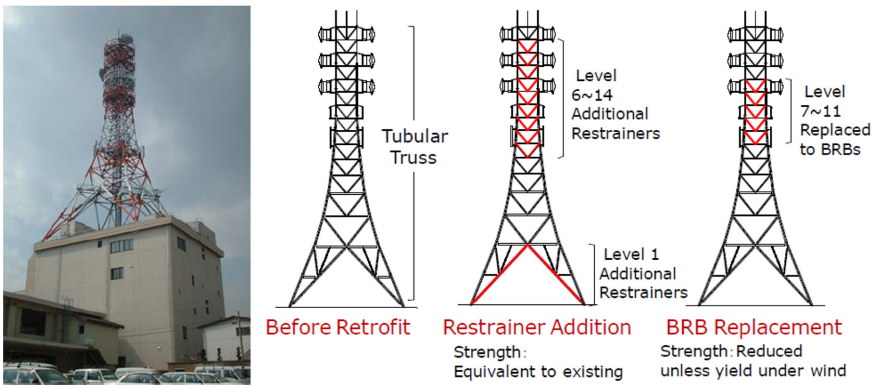


Figure 3.8. Retrofitted Communication Tower and Retrofit Options (Wada and Takeuchi, 2017).

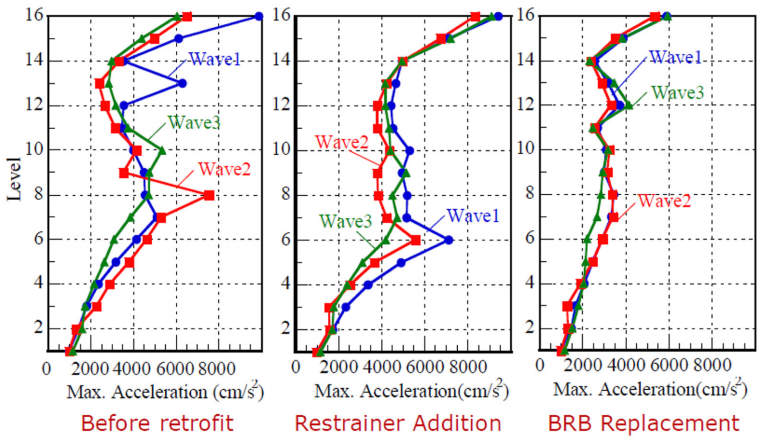


Figure 3.9. Comparison of retrofit Effects (Wada and Takeuchi, 2017).



Photo 3.3. Seismic Retrofit of Tower with BRB (Wada and Takeuchi, 2017).

Acknowledgements

This study has been partially supported by Prof. Toru Takeuchi, Tokyo Institute of Technology. The author is grateful for his technical supports.

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