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Effect of the Height Increasing on Steel Buildings Retrofitted by Buckling Restrained Bracing Systems and TTD Damper

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A B S T R A C T

The behavior of conventional braced frames are not the same in tension and compression. This problem can be improved by prevention of buckling under compressive loads, which is called buckling restrained brace (BRB). In this field, TTD metal damper also have attracted much attention due to simplicity in construction and execution. This damper is recommended because of accessing to better performance than BRB and also having easier construction technology and consequently being cheaper thus possibility of making it becomes feasible in countries without complex technologies. In this research, three steel structures with three, five and eight stories that require retrofitting, are retrofitted using buckling restrained brace and TTD metal damper separately, and are compared before and after the retrofitting using nonlinear dynamic analysis in PERFORM 3D software. Finally, the effects of this systems in reduction of structure displacement, reduction of energy dissipation due to nonlinear behavior in main members of structure, and increasing of performance level is inspected. The observation of both systems results imply that with increasing the number of building stories, expressed positive effect is reduced which indicates more effect of this energy dissapation systems in short-order structures.

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1. INTRODUCTION

Design of common buildings in regions that prone to have earthquake should be in a manner that their response against severe earthquakes comes in inelastic limit which is suitable economically. In the past, all structures were placed on elastic limit and designed based on region seismic intensity and structure importance, but at present the seismic and economical design is necessary to take advantage of energy absorbability behavior with inelastic deformations. Seismic design of structures usually is based on this fact that members anticipate in structure that show inelastic behavior in severe earthquakes and absorb seismic energy. In recent years, various and new methods were invented so that they have passed completely retrofitting traditional methods, i. e. increasing of structure capacity (increase in structure strength, local modification of structure components, increase in structure stiffness and etc.) and earthquake requirement reduction method by dampers and braces is selected as effective way for this purpose.

Among braces, buckling restrained braces (BRBs) are used as inactive control systems of energy dissipation in buildings seismic retrofitting. Unlike conventional braces, these braces have symmetric hysteresis loop and have the mechanism that prevent their buckling under compression load especially in periodical loading like earthquake, and yield before buckling and consequently all section capacity is used for energy dissipation (both in tension and compression).

In Figure 1.a the model of conventional brace, due to compression axial force (p), and displacement (δ), is shown. According to the figure brace is buckled and plastic hinge, in the middle of beam, is appeared. Thus, the resistance capacity of the brace is reduced. Also, in Figure 1.b the model of BRB due to compression axial force (p), and displacement (δ), is shown. According to this figure there is no buckling in brace, and thus the resistance capacity of the brace dose not reduce.

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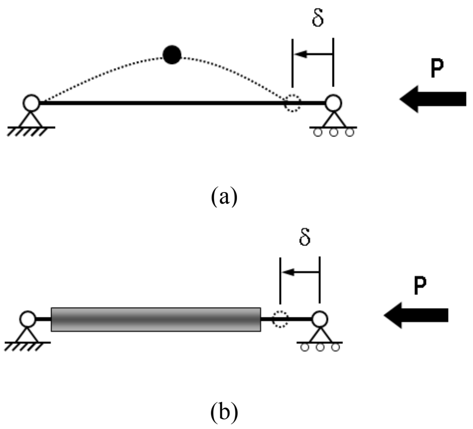


Figure 1. Brace due to compression axial force (p), and displacement (δ): a) conventional brace and b) BRB [1]

It is noteworthy to mention that one of the shortcomings of BRB is that this brace is monopoly of private company and construction and installing of them require more accuracy and endurance than other braces. Also, high expenditures for using of this bracing system in seismic retrofitting of structures do not always have acceptable economic justification.

In some countries, utilization of some structures retrofitting systems such as BRB is not possible because of nonexistence of required facilities and complex technology of construction. As a result, we can overcome mentioned necessities by finding more simple and effective method.

BRBs which have high stiffness and energy depreciation capability at first were inspected by Japanese researchers in 70's. Wakabayashi, et al. constructed braces by metal flat plates and placed them between precast pair panels of reinforced concrete. They obtained brace strength in compression higher than brace strength in tension in high deformations levels. They developed buried metal core idea in metal section full of concrete in continuation of their investigation [2].

Gradually, more extensive research was performed on this type of brace. Fujimoto, et al. in 1988 studied behavior of BRB with center core covered by metal cover that was filled by mortar. They performed some tests with various sizes of metal cover and developed design standards both for strength and stiffness of cover [3].

In 2005, Kim and choi provided a method for design of frames with BRBs using the hysteresis of energy spectrum. In this method, it is supposed that beams and columns remain in elastic state under gravity loads and energy depreciation and their damages happen only in BRB [3].

Ariyaratana and Fahnestock found that saving strength which is produced by members except BRB in resistant system against lateral load can improve seismic performance of BRBs [4].

Terán-Gilmore and Ruiz-García studied utilization possibility of BRB as a retrofitting plan for present multi-span and multi-story structures by analytical study. For this purpose, they inspected seismic response of four 2-dimensional frames in region with high ductility before and after the utilization of BRB. They found that relative displacement value of stories in frames of BRB is decreased [5].

Sahoo and Chao inspected plastic design method based on performance according to the energy balance, predefined target displacement and yield mechanism for accessing to predictable behavior of BRBs by incorporating inelastic specifications in design [6].

The new type of dampers namely TTD metal damper is another inactive control system of energy dissipation that in addition to low expenditure, have simple construction technology and acceptable performance. This damper is introduced for achieving better performance than BRB until its construction possibility becomes feasible in the most simple construction sites with minimum facilities and without requirement to advance construction technology.

In Figure 2, the example of displacement-load curves (Q - δ) obtained from cyclic tests related to TTD metal damper is shown. All curves were normalized by dividing long axis into yield displacement δy and dividing width axis into yield load Qy. It is seen that the damper demonstrate very stable hysteresis behavior and loops shape is very close to rectangular that is indicative of very high capability of damper for energy dissipation.

Celiment in 2009 produced a new steel inactive damper [7]. This damper like ordinary bracing install inside the structural frame diagonally. Tapes behave as a set of fixed-ended beams and deform with doubled curvature and consequently waste the energy via shear-flexural yielding.

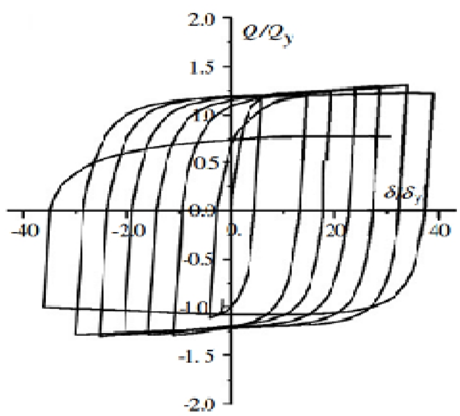


Figure 2. Example of normalized curve Q-δ of TTD damper obtained from the test [7].

2. CONSTITUTIVE COMPONENTS OF BRB

One type of constrained brace against buckling is shown in Figure 3. It is seen that this brace is composed of three main parts:

1. Metal core which is undertaken to endure the axial loads.
2. Metal cover and confining concrete that prevents the buckling of core element.
3. Separator substance which is prevented from interlocking between confining concrete and center core along member axis.

3. CONSITUTIVE COMPONENTS OF TTD DAMPER

According to Figure 4, this damper is composed of two hollow ordinary steel structural sections that one of them is placed into another one, and is named box-in-box damper [7]. There are some cut fissures in outer hollow section of this damper, and some tapes are remained between fissures. This outer section is connected to the inner hollow section by welding.

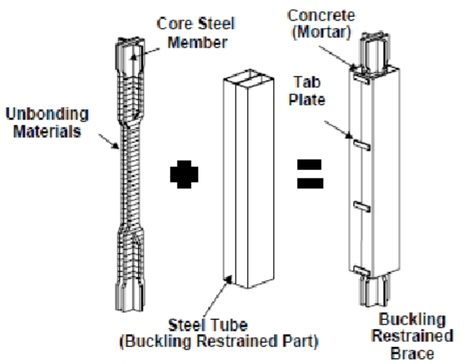


Figure 3.Various components of constrained braces against buckling [8,9]

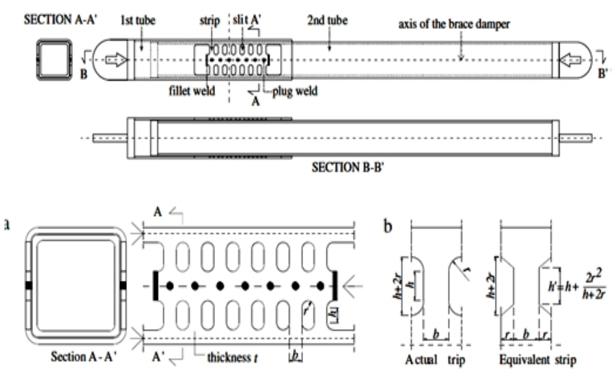


Figure 4. a) General schematic of TTD damper, b) details of wasting part of energy and c) equivalent tape

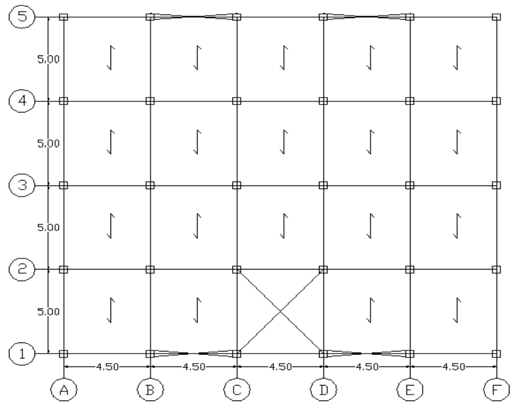


Figure 5.Structural plan of buildings

4. MODEL EVALUATION

In this research, three steel buildings with similar plan and three, five and eight stories are used for comparison of seismic performance evaluation of steel buildings retrofitted by BRB systems and TTD yielding damper.

Evaluation of seismic bearing of these buildings is performed according to the seismic retrofitting procedure of present buildings (publication 360) that is virtue of publication FEMA356 [10, 11].

In this research aim of retrofitting is selected base retrofitting.

4. 1. Introduction of Considered Structural Plan

According to Figure 5 total dimension of plan is 20*22.5m, and architectural area is 450 m^2. Height of first story is 3.5 meter and other stories are considered 3.2 meter. Direction of all joists is in Y axis direction.

4. 2. Design of Considered Models

In this research, design of considered building is performed by SAP2000 software and standard 2800, first edition [12, 13], then, its seismic evaluation is inspected by PERFORM 3D software. Having structure that required retrofitting, each of buildings has been retrofitted by BRB and TTD, and then seismic performance of buildings has been compared before and after retrofitting [14]. Considered specifications are provided for this issue as follows.

Region from the view point of zoning of earthquake relative danger is placed on area with average relative danger and also ground type is seemed type III. Consequently, reflection coefficient plot of building is obtained according to the standard 2800, third edition, and design response spectrum is obtained based on publication 360 to perform earthquake lateral loading (danger level 1) according to the value of design base acceleration (A=0.25) [10,15].

Structural system of building in x direction is moment-resisting frame + brace and in Y direction is moment-resisting frame. Diaphragm is considered as block joist and is modeled rigidly. Furthermore, present sections are considered IPE for beams and hollow box sections for columns and doubled channel for braces.

4. 2. 1. Principles of Design In structures design and their bearing elements some criteria should be considered. Importance of these criteria depend on structure type, constitutive components of substance that structure is constructed from it and utilization method. General criteria that can be considered in design of one structure are strength, plastic yielding, stability, deformation, dynamic behavior, ductility, and fatigue criteria.

4. 2. 2. Design and Modeling of BRB There is not capability of equivalent static analysis for obtaining the sections of BRB components in PERFORM 3D software, therefore, design should be done firstly by the software that can perform this analysis. In this investigation, SAP 2000 is used and dimensions are determined.

In structures such as braces in which buckling occurrence or instability is main factor of destruction, criteria of design controller will be stability. BRBs have property of very high energy dissipation. For this reason, BRBs were reposed in set of viscous and hysteric and frictional dampers in the past and their design was performed as design of mentioned damper. Researchers found based on the advances in this field that this design method is not so true, and nowadays, design of BRBs are performed like eccentric braced frame with this difference that local collapse are not happened when earthquake occurs, and the brace is changeable at need which is more simple than links change in eccentric braced frame.

Design standards of BRBs have not been covered in any of reliable codes completely. But suggestions is introduced in procedure FEMA-450 [16] and also in seismic part of AISC (2005) code [17] (steel code of USA) for design of these frames. It is quote worthy that BRB element is present in menu of PERFORM 3D software for design and this element is used in this research in PERFORM 3D software according to the written FEMA procedure.

4. 2. 3. Design and Modeling of TTD Damper Retrofitting should be performed according to conducted seismic evaluation on present condition of structures and need distinguishing to their retrofitting. Dampers modeling are conducted according to the produced code points in publication 360.

Before dampers modeling, their design should be done using proper method. Considered design method is based on UBC code for dual systems in which moment-resisting frame tolerate vertical load and damper-brace set endure lateral loads. One method for structure design which is equipped with TADAS is described by Tsai et al. here; this algorithm is used because of general similarity of TTD damper with TADAS [19]. In Figures 6, 7 and 8 Tsai damper design algorithm is shown and summary of this method is demonstrated in continuation [18]. Modeling of damper is performed in PERFORM 3D after its designing. For modeling of any type of damper depending on deformation, it is enough that their deformations are considered completely in modeling. Furthermore, if interaction of axial load with shear and bending or two-side deformation are present, these factors must be considered.

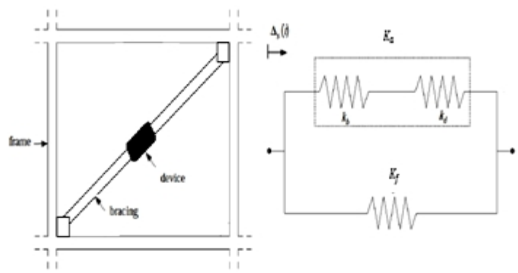


Figure 6. Frame modeling which is equipped with TTD damper with spring [18]

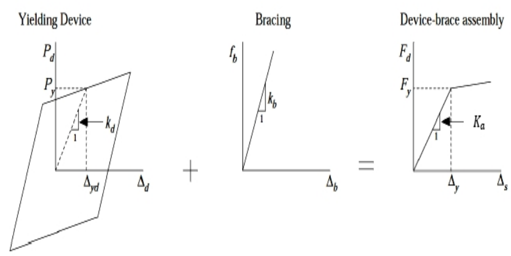


Figure 7. Load-displacement schematic plot of brace-damper set from series combination of damper and brace [18]

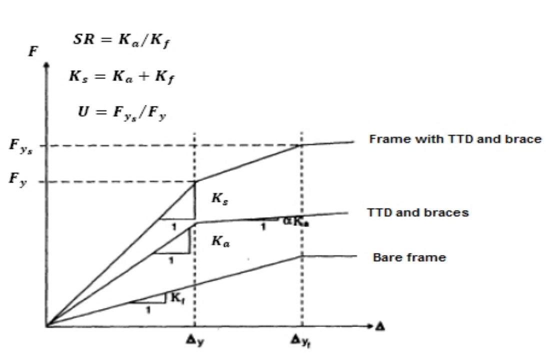


Figure 8. Load-displacement schematic plot of frame system which is equipped with brace-damper set from parallel combination of frame and brace-damper set [18]

According to the mechanical specifications of TTD damper, its deformation-force relation depends on relative deformation between two ends of equipment, and its reaction is independent of relative speed between two ends of equipment and vibration frequency, and there is no interaction between axial load and shear and bending or existence of two-side deformation in it [18].

There are different elements in PERFORM 3D software for modeling of any types of energy dissipation facilities that seismic isolator elements are used for modeling of TTD metal dampers in this research.

5. METHODS OF ANALYSIS AND RESULTS EVALUATION

In this research, nonlinear dynamic analysis is used for comparison of seismic performance of steel buildings before and after retrofitting by BRB and TTD systems, and analysis process along with results are demonstrated in continuation.

5.1. Results of Nonlinear Dynamic Analysis Nonlinear dynamic analysis is used for behavior evaluation of structures which are affected by earthquake effect. Nonlinear dynamic analysis is performed as spectral or time history. In this research, time history method is used [4, 19]. In order to conduct this analysis in PERFORM 3D software, 7 accelerometers pair according to the provided standards in publication 360 are used: Corralitos, Imperial Valey, Kobe, Kocaeli, Loma Prieta, Northridge, and Trinidad. With this description, we will have 14 loading cases of nonlinear dynamic analysis that mean-max method is used for performance evaluation of structures after performing the analysis related to any of loading cases.

Considered gravity load combination for nonlinear dynamic analysis is included in two states as follows according to the publication 360 which is used in this research [4].

$$Q_G = 1/1[Q_D+Q_L] \quad (1)$$

$$Q_G = 0/9\ [Q_D] \quad (2)$$

Q_D is dead load and Q_L is live load according to the standard 519 that is considered equal to 25% of design live load [11].

5.2. Scaling of the Accelerometers Accelerometers have been scaled based on written method in standard 2800. Selected accelerometer pairs must be scaled according to the following method [15]:

a. All accelerometers scale to their maximum value, it is meant that maximum acceleration of all become equal to gravity acceleration (g).

b. Acceleration response spectrum of any of scaled acceleration pairs is determined by considering damping ratio of 5 %.

c. Response spectra of each acceleration pair are combined with each other using square root of the sum squares (SRSS) and finally a compound spectrum is constructed for each pair.

d. Determined scale coefficient should be multiplied by scaled accelerometers in part a, and must be used in dynamic analysis.

SeismoMatch software is used for scaling and equalization of accelerometers. Comparison of response spectrum of 7 scaled accelerometers with 0.25 times of standard spectrum is shown in Figure 9 [21].

5.3. Time History Comparison of Roof Mass Center Deformation Before and After Retrofitting of BRB and TTD Systems In Figures 10-12, time history of roof mass center deformation before and after structure retrofitting in moment resisting frame + brace direction and moment resisting frame direction is compared under Corralitos earthquake for nonlinear dynamic analysis and under 1st gravity load combination.

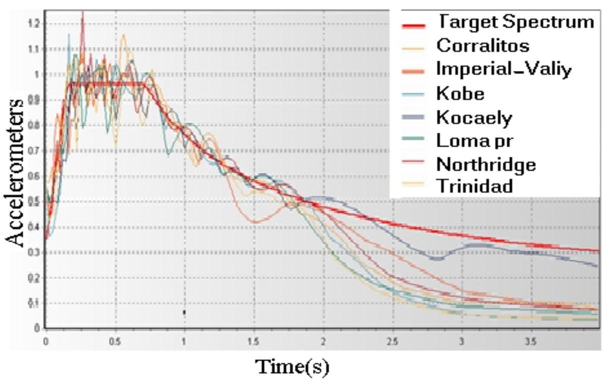
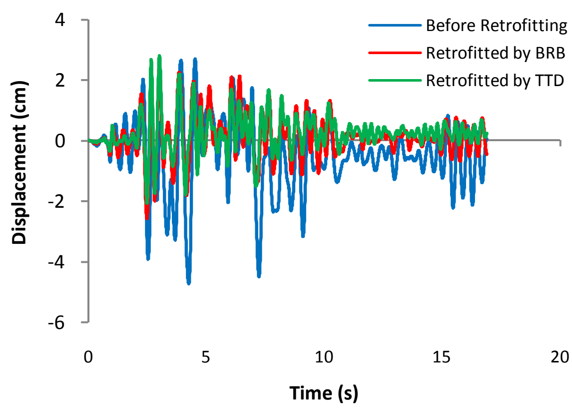
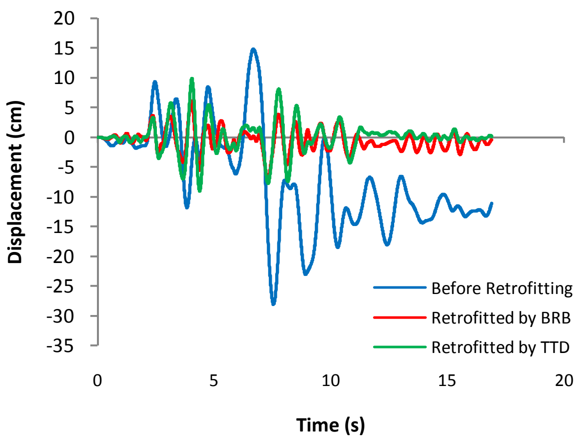


Figure 9. Comparison of response spectrum of 7 scaled accelerometers with ¼ times of standard spectrum

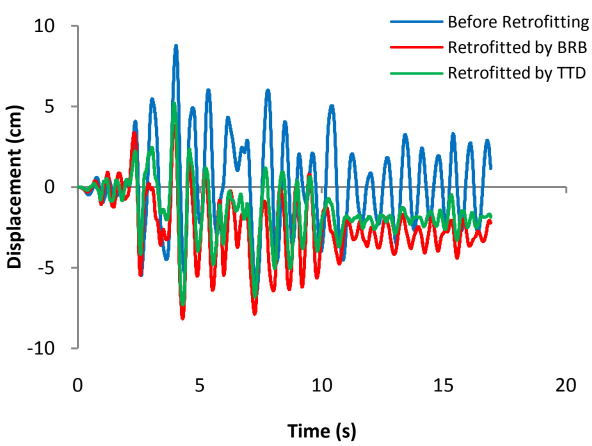


(a)

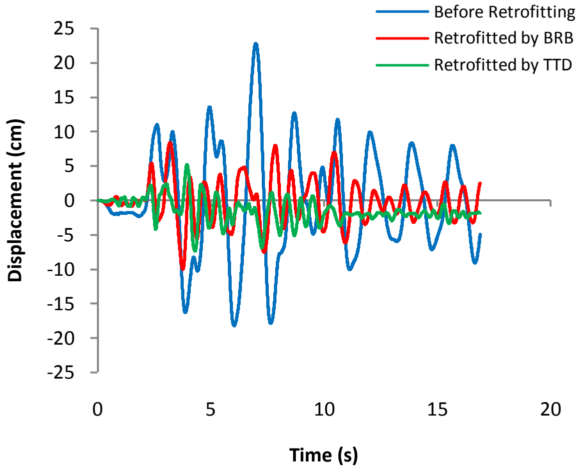


(b)

Figure 10. Time history comparison of 3-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction

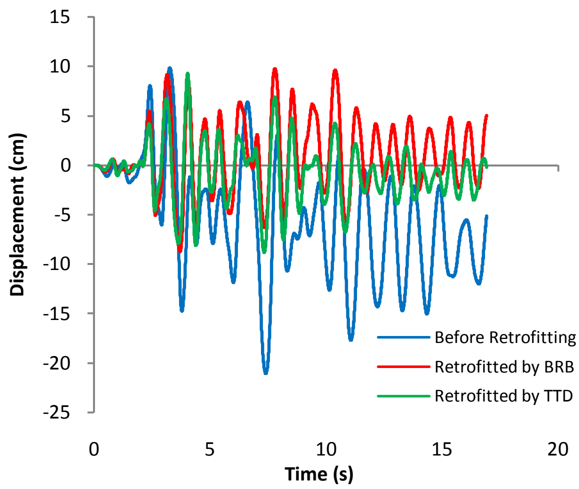


(a)

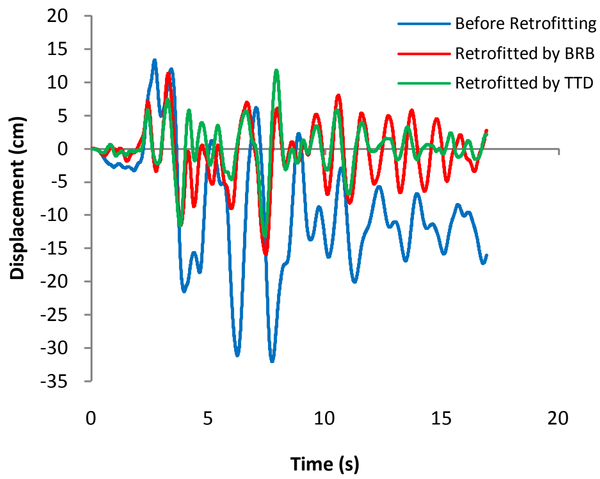


(b)

Figure 11. Time history comparison of 5-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction

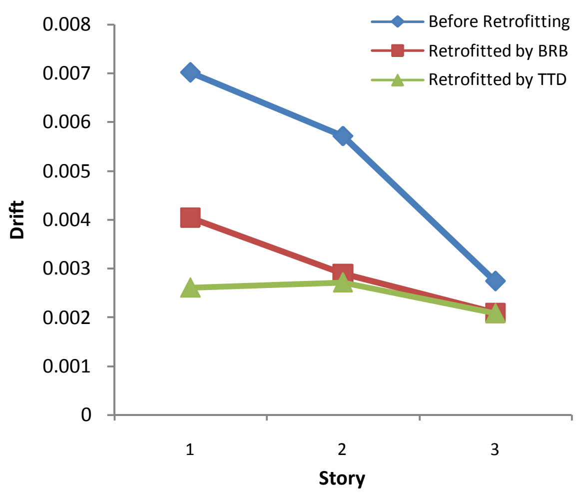


(a)

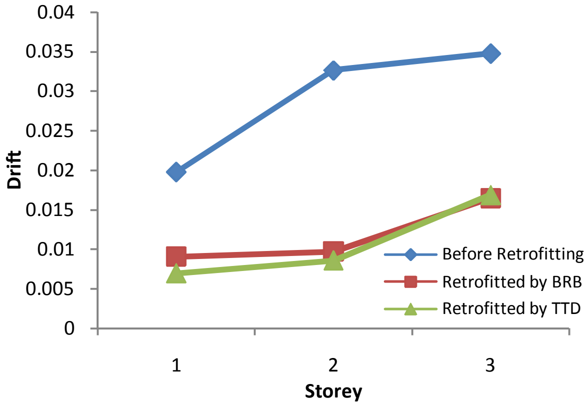


(b)

Figure 12. Time history comparison of 8-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction



(a)



(b)

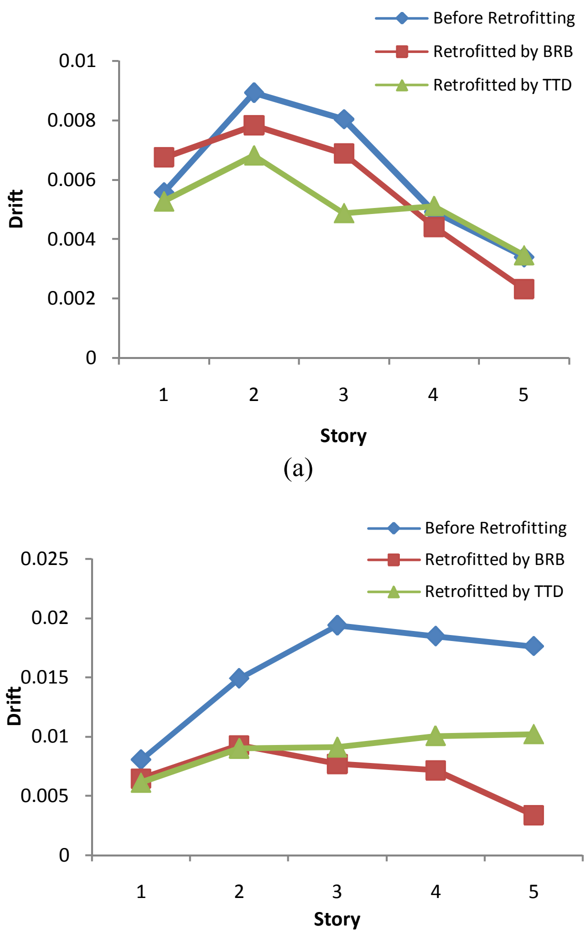
Figure 13. Comparison of stories drift, 3-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction

5.4. Comparison of Stories Drifts Before and After Retrofitting by BRB and TTD Systems

Stories drift (maximum relative displacement of stories) are shown in Figures 13-15 under Corralitos earthquake in moment resisting frame + brace direction and moment resisting frame direction under 1st gravity load combination [4, 22].

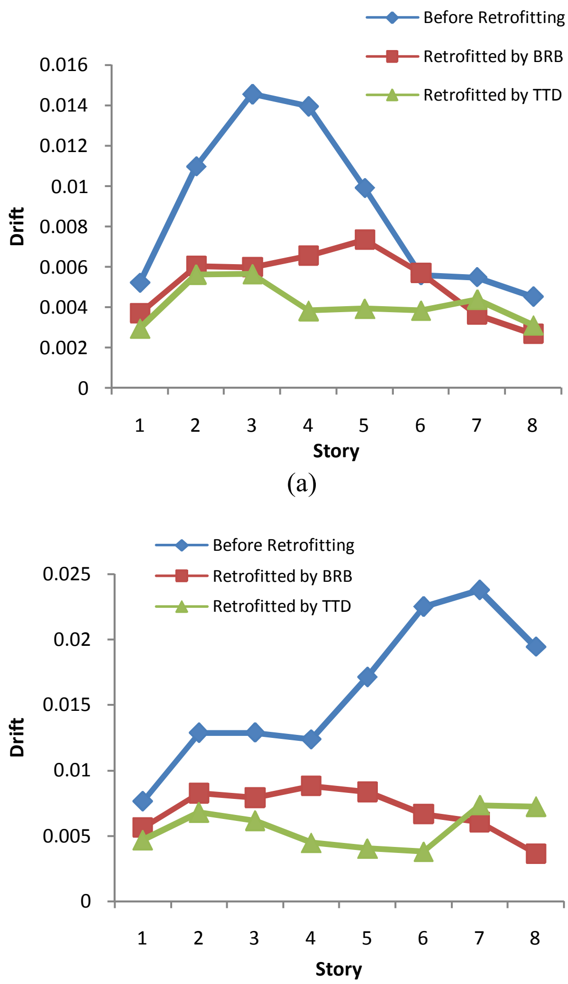
5.5. Comparison of Energy Dissipation Portion in any Main Members of Structure Before and After Retrofitting by BRB and TTD Systems

Plots of portion percentage of elastoplastic energy dissipation in members are shown in Figure 16 before and after retrofitting under Corralitos earthquake in the case of using 1st gravity loading combination for all buildings [23].



(b)

Figure 14. Comparison of stories drift, 5-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction



(b)

Figure 15. Comparison of stories drift, 8-story building: a) In moment resisting frame + brace direction, b) In moment resisting frame direction

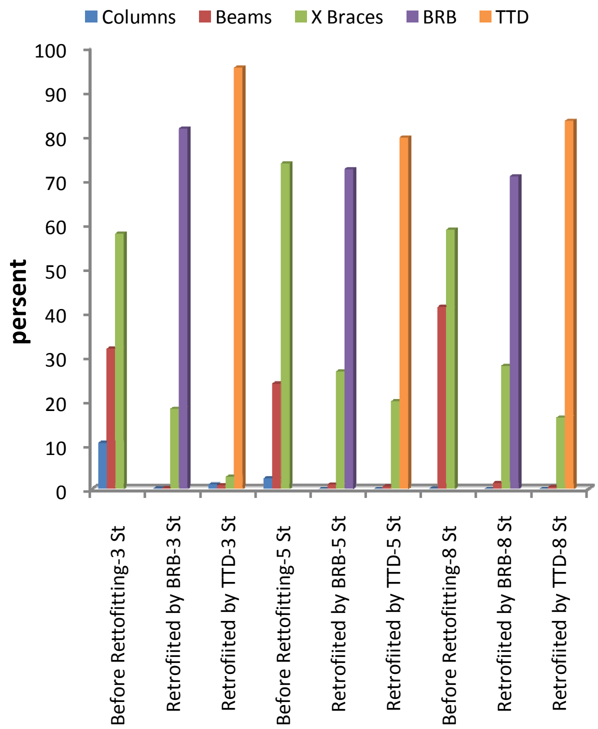


Figure 16. Portion percentage of energy dissipation of any main member of structure for all buildings

6. CONCLUSION

After utilization of BRB brace and TTD damper in considered structures, it is seen that important indexes such as deformation of roof mass center and stories relative deformation is decreased significantly that mentioned variation is more in moment resistant direction than direction of moment resistant + brace. This issue demonstrates very desirable performance of these systems in retrofitting of structures.

Results imply that in considered structures, total energy dissipation is due to member nonlinear behavior in beams, columns and cross braces, while major part of energy dissipation after retrofitting by BRB brace and TTD damper is due to nonlinear behavior of members in these systems and consequently, portion of other structural members is decreased significantly.

Plastic joints in considered structures is created in beams and braces before retrofitting, while major part of plastic joints is produced in these systems after retrofitting by BRB brace and TTD damper and consequently plastic joints is decreased significantly in other members of structures (beams, columns and braces).

Result comparison of the buildings 3, 5, and 8 stories in both systems also imply that with increasing the number of building stories, because the mass of the building creates a problem, expressed positive effect is reduced which indicates more effect of this energy dissipation system in short-order structures.

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Nonlinear Dynamic Analysis

چکیده

رفتار قاب‌های مهاربندی شده متداول در کشش و فشار یکسان نیست. این مشکل را می‌توان با جلوگیری از کمانش مهاربند تحت بارهای فشاری، بهبود بخشید. چنین مهاربندی، مهاربند مقید در برابر کمانش یا مهاربند کمانش ناپذیر(BRB) نامیده می‌شود. همچنین در این عرصه میراگر فلزی نوعTTD به دلیل سادگی در ساخت واجرا از توجه زیادی برخوردارند.. این میراگرباهدف دستیابی به عملکرد بهتر از مهاربند BRB وهمچنین داشتن تکنولوژی ساخت ساده تر و در نتیجه ارزان تر، معرفی شده است تا امکان ساخت آن در کشورهای فاقد تکنولوژی های پیچیده امکان پذیر باشد. در این مقاله سه ساختمان فولادی سه ،پنج و هشت طبقه که نیاز به بهسازی دارند را به صورت جداگانه با مهاربند کمانش ناپذیر و میراگر TTD بهسازی کرده و آنها را در دو حالت قبل و بعد از بهسازی و با استفاده از تحلیل دینامیکی غیر خطی در نرم افزارPERFORM 3D مورد مقایسه قرار می دهیم. در نهایت تاثیر این سیستم ها درکاهش تغییر مکان سازه، کاهش اتلاف انرژی ناشی از رفتار غیرخطی در اعضای اصلی سازه و افزایش سطح عملکرد سازه مورد بررسی قرار می گیرد. همچنین نتایج نشان می دهد که با افزایش تعداد طبقات ساختمان تاثیرات مثبت بیان شده ،کاهش می یابد که این نشان دهنده ی تاثیر مناسب تر این سیستم های اتلاف انرژی در سازه های کوتاه مرتبه می باشد.

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