Araştırma Makalesi / Research Article

Analysis of different cross-frame placements to enhance torsional irregular buildings against structural failure under earthquake bidirectional loadings: A case study

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Abstract

Cross bracing frames (CFs) are employed as traditional passive energy dissipating devices, which are placed into the moment-resisting frames of the Benchmark building picked for analysis purposes. These devices are widely used, easy to construct, and inexpensive to contribute better seismic protection for existing and new buildings than complex control systems like active/passive Tuned Mass Dampers (TMDs) and so on. Therefore, in this research, the best three-predetermined CFs placements are selected. The time history analyses are made under bi-directional seismic loads such as two orthogonal excitations of El Centro in 1940, North-Ridge in 1994, and Kocaeli, Turkey in 1999. In conclusion, obtained results find out that while CFs placements into the structure can be significantly eliminating the eccentricity in the structure plan by dissipating especially torsional responses (approximately between 30% and 50% decrease) with a right engineering design perspective like Case 3, they cannot be successful enough to reduce the torsional responses without the right design vision such as Case 1 and Case 2. Therefore, Integrating CFs placements to the structure for minimizing the structural response is not always comprehensive to make the structure durability against torsional irregularity unless placed with the right engineering decision.

Keywords: Torsional Irregularity, Time History Analysis, Performance Evaluation, Cross Frame Placement.

Çift yönlü deprem yüklemeleri altında eksentrik binalar için yapısal hasarlara karşı bina performansını artırmak için farklı çapraz destek profilleri yerleşimlerinin analizi: Bir vaka çalışması

Öz

Çapraz Destek Profilleri (ÇDP), günümüzde özellikle eksantrik binaları deprem esnasında burulmaya karsı korumak için kullanılan yöntemlerden biridir. Bu yöntem, aktif / pasif Ayarlı Kütle Damperleri (AKD) gibi karmaşık kontrol sistemlerine kıyasla, mevcut ve yeni binalar için daha iyi bir sismik korumaya katkıda bulunmak için yaygın olarak kullanılır. Çünkü yapımı kolaydır ve uygulaması diğer yöntemlere göre daha ucuzdur. Bu nedenle, bu araştırmada, önceden belirlenmiş en iyi üç ÇDP yerleşimleri seçilerek, iki yönlü sismik yükler altında sismik analizleri, 1940'da El Centro, 1994'te North-Ridge ve Kocaeli 1999 deprem dataları altında yapılmıştır. Elde edilen sonuçlara göre ÇDP'ler yapıya yerleştirilirken Durum 3'teki gibi doğru bir mühendislik tasarım perspektifi ile birlikte yapıda burulma tepkilerini (yaklaşık olarak %30 ile %50 arasında) azaltarak yapı planındaki eksantrikliği önemli ölçüde ortadan kaldırabilirken, doğru tasarım vizyonu ile yerleştirilmeyen ÇDP'ler yani Durum 1 ve Durum 2'da olduğu gibi burulma etkilerini bazı yükleme durumları için azaltacak kadar başarılı olamamışlardır. Bu nedenle, yapısal tepkileri en aza indirmek için ÇDP'leri yapıya entegre etmek, doğru mühendislik perspektifi ile yapılmalıdır. Aksi takdirde ÇDP'ler yapıdaki burulma düzensizliği etkilerini azaltmadığı gibi binada burulmadan dolayı oluşabilecek yapısal hasar olasılığının da artmasına neden olabilmektedir.

Anahtar kelimeler: Çapraz Destek Profilleri, Eksentrik Binalar, Performans Analizi.

1. Introduction

Existing building stock in Turkey mostly has an eccentric plan configuration, called torsional irregularity in the plan, that making the buildings highly vulnerable to strong dynamic excitations caused by severe earthquakes or strong winds. The torsional irregularity is mostly the main failure reason for eccentric buildings during an earthquake, which does not only have devastating effects in the torsional direction but also leads to excessive destructive forces in the lateral directions. Therefore, ignoring such irregularity in the seismic analysis may lead to unexpected damages and losses [1-3].

Seismic risk evaluation is a fundamental necessity in long-term and inclusive seismic codes since population concentration is increasing day by day in earthquake-prone areas. Consequently, understanding earthquake dynamic effects on building stocks is vital to keep the public secure and safe [4-6]. The earthquake dynamic effects on a structure induce horizontal inertia forces acting through the center of mass. At the same time, the vertical members resist these forces through the center of rigidity. In many real-life structures, these reverse forces are predominantly not coincident. The lack of coincidence between the centers of mass and rigidity produces eccentricities, which cause an undesirable torsional response. The term "lateral-torsional coupling effect (LTCE)" is used when the torsional response is coupled with the lateral response [7,8].

Improvements in the structural material with the help of using advanced technologies, modern buildings become taller and taller and get more flexible utilizing innovative materials. This inclination makes the buildings more vulnerable to dynamic excitations, especially for those having torsional irregularities in the plan or elevation when torsion becomes a dominant matter. Torsional irregularity exists due to the lack of coincidence between the center of mass (CM) and rigidity (CR) that is the center for the distributed lateral load-bearing components in a floor [9,10]. Under these circumstances, the buildings have a tendency not only to rotate but also to deflect laterally in two orthogonal directions when going through dynamic loading, see Figure 1.

(a)

(b)
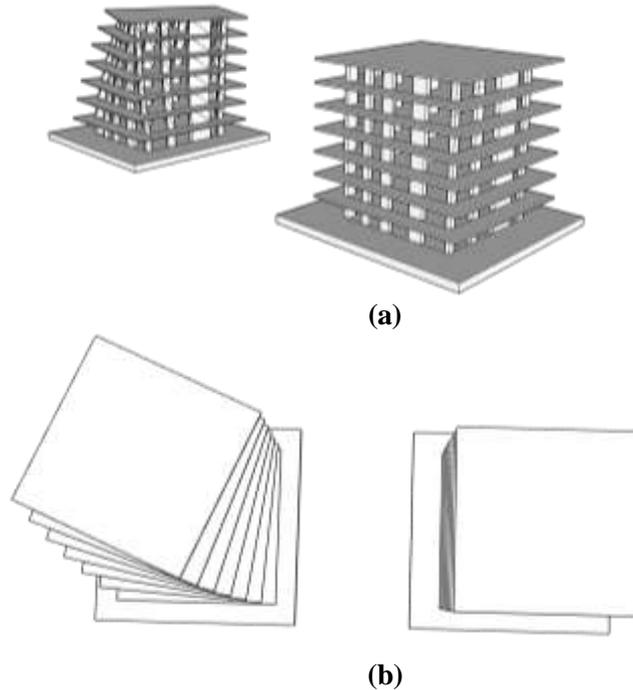
Figure 1. A demonstration of civil structure with its torsional response: **(a)** elevation and **(b)** bird's eye view [11]

A lot of modern control systems have been introduced into the literature in the last two decades to keep the structures secure when earthquakes excite them. The most widely preferred and used passive control systems by engineers and designers is a tuned mass damper (TMD) comprised of additional appropriate mass, damping, and stiffness to the primary system, excluding any external power supply [12]. However, it has some drawbacks. First, it is operative only in the fundamental tuning frequency of the structure; thus, it can be valid only in the low-frequency spectrum range. Second, it is not convenient

for all the modes to utilize other than the tuning mode, which is generally is the first-mode of the structure because it does not have significant effects in the case of an earthquake. That is why it is first introduced multi-tuned mass dampers (MTMD) to use for eliminating the drawbacks of employing a single TMD [13]. Owing to the MTMD, it becomes more comprehended as compared to a single TMD by tuning it to different natural frequencies (modes). Therefore, it becomes more serviceable and improves stability at a wide frequency spectrum range [14-16].

Unlike the modern innovative control systems, the CFs behave as the primary members to resist the twist of the structures such as steel buildings and bridges when they are integrated into the load-carrying systems. The bracing system is a natural and essential approach to improve the security and robustness of the buildings having torsionally irregular plan configuration when withstanding against earthquake loadings[17,18]. Because it plays a vital role in an increase not only in the load capacity by laterally and torsionally, but also reduces the absolute distance between the center of mass (CM) and rigidity (CR) when it is placed appropriately in the plan and elevation layout. It might be a v-, inverted v-, k- or x-bracing for steel frames [19-21] or masonry infill-wall for reinforced-concrete structures [22, 23] respectively.

CFs placements as a structural member of the structure are expected to improve lateral load capacity and torsional loading capacity of the structure; however, sometimes they can cause to increase unevenly distributed stiffness and strength in the plan or elevation in the structure. Therefore, the study's scope is to investigate and evaluate the CFs placements, whether designed with or without a good engineering design perspective on structural performance. With this purpose, in this research, the Benchmark 9-story steel building is selected as a model structure for analysis purposes where each floor has three degrees of freedom (two translational and one rotational). There are three cross frames placements into the Benchmark 9-story steel structure's MRFs are pre-determined by the consideration of eliminating eccentricity between CM and CR of each floor. The three pre-determined cross frames (CFs) are determined by eliminating eccentricity and are employed to control undesirable lateral and torsional vibration under selected real saved earthquake ground motions. In conclusion, the research focus is on the performance evaluation of CFs placements and their contribution to the structure's performance. Integrating CFs to the structure for lessening the structural response is not always comprehensive to improve the structural stability against torsional irregularity unless placed with the right engineering decision.

2. Material and Methods

2.1. Design Properties of Benchmark Building

It has simply connected-columns to the ground, and they are made of 345 MPa steel. It has the 9.15m long-bays, which are five bays in both orthogonal directions. The columns and beams are comprised of wide-flange shapes, and the columns' orientation in the plan is demonstrated in Figure 2a. Moment frames (MFs) and simple frames (SFs) are assigned see Figure 2b. The interiors bays of the structure are simply connected to the composite floors, which are assigned as rigid diaphragms that provide the same response for each node within a story level during dynamic excitation. The bays and composite floor decks for each level are made of 248 MPa steel, and they are acting together thanks to rigid diaphragms. The lumped mass of the ground level, the first level, the second through eighth levels, and the ninth level are in order 9.65×105 kg, 1.01×106 kg, 9.89×105 kg, and 1.07×106 kg. The total mass of the whole structure above the ground level is 9.00×106 kg. A-A axis showing columns-and beams connections is portrayed in Figure 2c. To further the structural design and structural property, the readers refer to [24,25].

It is assumed that each floor has a rigid diaphragm behavior that can provide to transfer all loads directly to the columns. Each node on a floor has the same response employing the diaphragm under earthquake loadings. The structure is simplified and represented by two orthogonal (x and y) and one rotational (θ) degree of freedom in each story. Moreover, a 10% moment reduction at the splices is assigned, and shear deformation in elements is neglected. For moment frames (MFs) and simple frames (CFs), the lateral stiffness capacity is calculated respectively by using Eqs. (1) – (2) [26] and Eq. (3)

(a)

(b)

(c)
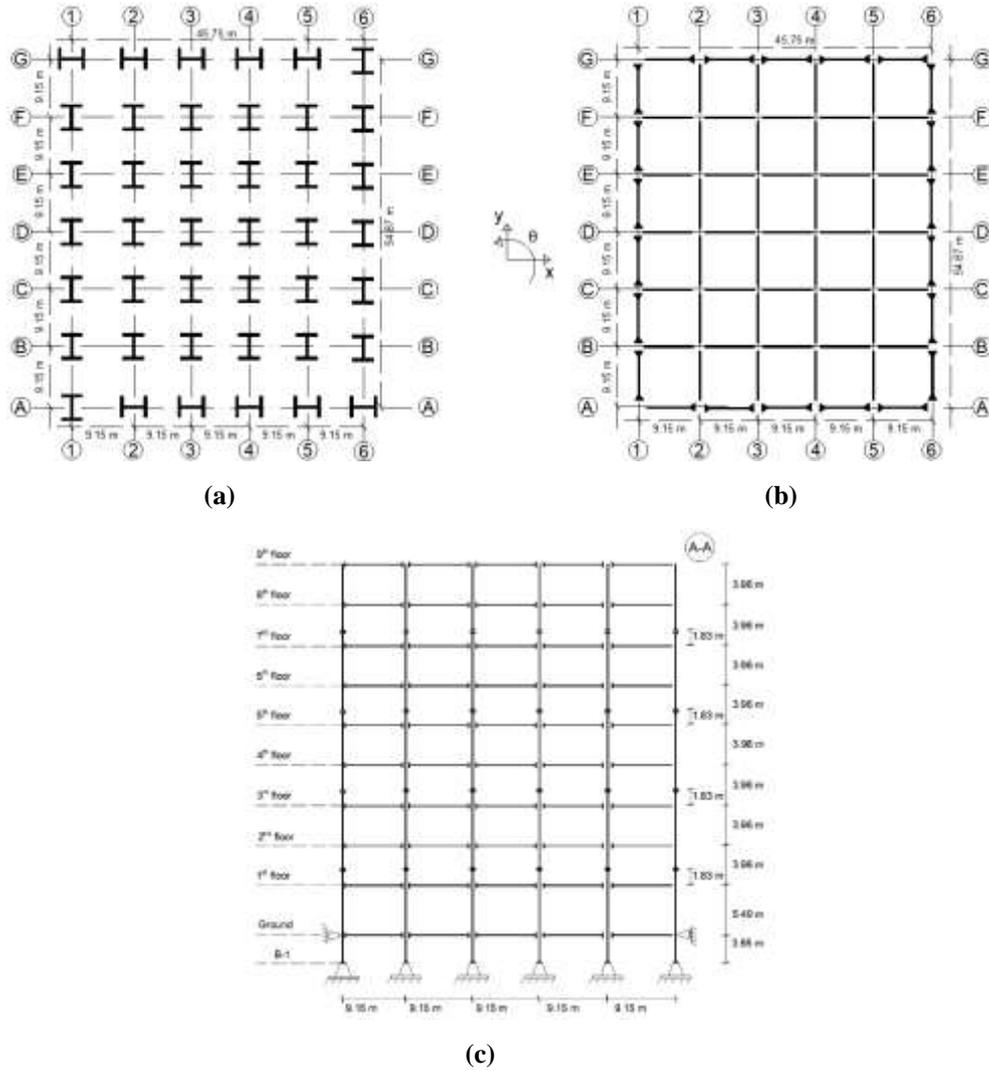
Figure 2. The structural details of Benchmark buildings modified it from [25]: **(a)** The orientations of columns in the plan, **(b)** Beams and columns connection types in the frames, and **(c)** Elevation-views

$$k = \frac{24\,E\,I_c}{h^3}\frac{12\,\rho + 1}{12\,\rho + 4} \tag{1}$$

$$\rho = \frac{I_b}{4I_c} \tag{2}$$

$$k = \frac{3\,E\,I_c}{h^3} \tag{3}$$

where k is the equivalent stiffness For moment frames (MFs) and simple frames (CFs), ρ is the beam-to-column stiffness ratio, I_c and I_b are the moments of inertia of the beam and columns in a moment frame (MF), and h and E are, in order, the floor height and material elasticity. The structural property of the Benchmark building with cross frames is given in Table 1.

Table 1. The Benchmark building structural components and steel sections used in the braced frames

Story no	Heights (m)	Ext. Columns	Int. Columns	Beam	Brace
1	5.49	W14x370	W14x500	W36x160	HSS 14x14x7/8
2	3.96	W14x370	W14x500	W36x160	HSS 14x14x7/8
3	3.96	W14x370	W14x455	W36x135	HSS 12x12x5/8
4	3.96	W14x370	W14x455	W36x135	HSS 12x12x5/8
5	3.96	W14x283	W14x370	W36x135	HSS 12x12x5/8
6	3.96	W14x283	W14x370	W36x135	HSS 12x12x5/8
7	3.96	W14x257	W14x283	W30x99	HSS 10x10x5/8
8	3.96	W14x257	W14x283	W27x84	HSS 10x10x5/8
9	3.96	W14x233	W14x257	W24x68	HSS 8x8x1/2

2.2. Cross Bracing Frames into Steel Buildings

Cross frames into moment-resisting-frames (MRFs) of a steel structure can significantly improve the safety and stability of the structure by increasing lateral and torsional load capacity. The effectiveness of the cross frame can be controlled and improved when the cross frame must satisfy the design requirements [27]. In this research, cross frames are employed to control undesirable lateral and torsional vibration under selected real saved earthquake ground motions. For simplicity in the analysis of the Benchmark building with CFs placements, the CFs are idealized by using the equivalent compression strut.

2.2.1. Theory of the Equivalent Compression Strut

When computing the torsional stiffness of the cross frame, an elastic truss analysis is often employed [28]. For a tension-only system, the contribution of the compression diagonal is neglected, and the single diagonal model illustrated in Figure 3 is analyzed.
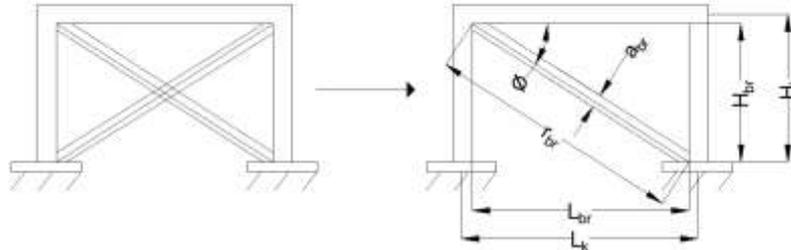
Figure 3. Cross frame design in compression

where $Ø$ is the angle between the height and length of the cross-frame member. H_{br}, H_k, and L_{br}, L_k are respectively the height and length of the equivalent compression strut and frame. The diagonal length of the cross frame is denoted as r_{br} in compression, the width of the strut is a_{br}. To determine the diagonal and rotational (according to [28]) stiffness of the cross frame are respectively as:

$$k_{br} = \frac{A_{br} E \cos^2(Ø)}{L_{br}} \tag{4}$$

$$\beta_{br} = \frac{E H_{br}^2 L_{br}^2}{\frac{2 r_{br}^3}{A_c} + \frac{L_{br}}{A_h}} \tag{5}$$

where k_{br} and β_{br} are the equivalent diagonal and torsional stiffness calculate when employing the cross frame into the moment frame (MF) considering only the axial stiffness of the members, E is the modulus of elasticity (200 GPa), A_c and A_h are respectively the area of the diagonal member and area of each strut.

2.3. The Selections of the CFs Placements in the Benchmark Building

In order to mitigate not only lateral vibrations but also twisting of the structure, there are three cross frames placements into Benchmark 9-story steel structure's MRFs that are pre-determined by the consideration of eliminating eccentricity between CM and CS of each floor. As seen in see Figure 4, the placements of Case 1 in the plan view are illustrated in section a and its corresponding A-A elevation views are provided in section b. Cross frames (CFs) are placed from ground level to the top floor without any discontinuity in the determined frames. For this reason, for Case 2 and Case 3, there are only plan views of the placement of cross frames provided, see Figure 4c and Figure 4d. In addition, the section properties of the Benchmark building structural components and used braced frames for each floor are tabulated in Table 2. For the cross-frame placements, the HSS section is selected with different section properties for each floor. Assuming that each cross-frame strut is connected to the main-frame as a pin connection and its damping ratio is taken by a 100% increase as compared to the Benchmark structure. In this research, three different placements of the x-bracing system, (Case 1, Case 2, and Case 3) will be taken into account of seismic analysis, and the most effective placement will be determined.

(a)

(b)

(c)

(d)
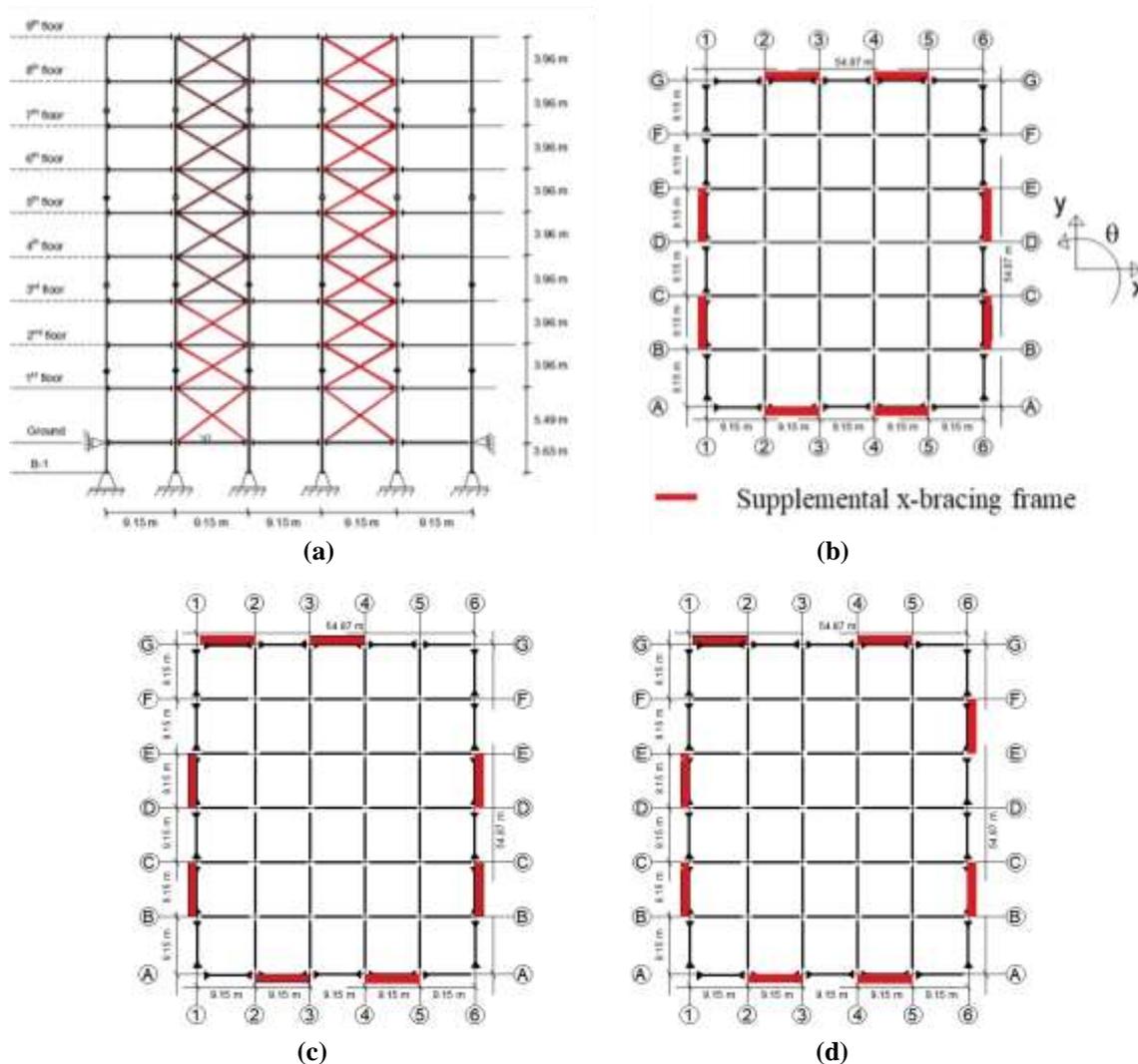
Figure 4. Different placements of the x-bracing system in moment resisting frames (MRFs): (**a**) A-A elevation view of Benchmark building, (**b**) in the plan view for Case 1 and x-bracing placement in the plan view of the Benchmark building for (**c**) Case 2 and (**d**) Case 3.

Table 2. The geometric property and the contributions of the used cross-frame systems into MRFs

Story no	Brace	Geometric property						Contributions		
		A_c (m)	A_{br} (m)	W (kg/m)	L_{br} (m)	r_{br} (m)	Angle (Ø)	W (kg)	Lateral Stiff. (N/m)	Torsional stiff. (N/m)
1	HSS 14x14x7/8	0.03	3.13	20.68	2.77	10.67	30	3530.70	1.06E+09	2.18E+10
2	HSS 14x14x7/8	0.03	3.13	20.68	2.77	9.97	23	3298.93	6.95E+08	1.39E+10
3	HSS 12x12x5/8	0.02	2.70	12.90	2.39	9.97	23	2057.84	4.41E+08	8.91E+09
4	HSS 12x12x5/8	0.02	2.70	12.90	2.39	9.97	23	2057.84	4.41E+08	8.91E+09
5	HSS 12x12x5/8	0.02	2.70	12.90	2.39	9.97	23	2057.84	4.41E+08	8.91E+09
6	HSS 12x12x5/8	0.02	2.70	12.90	2.39	9.97	23	2057.84	4.41E+08	8.91E+09
7	HSS 10x10x5/8	0.01	2.26	10.55	2.01	9.97	23	1682.96	3.43E+08	7.01E+09
8	HSS 10x10x5/8	0.01	2.26	10.55	2.01	9.97	23	1682.96	3.43E+08	7.01E+09
9	HSS 8x8x1/2	0.01	1.82	6.75	1.61	9.97	23	1076.78	2.21E+08	4.56E+09

2.4. Analysis Method

Time history analysis (THA) is dynamic analysis. Most of the seismic codes [29,30] discourage usage because of the long-time required in the simulation analysis compared to other under-recorded earthquake data. Response spectrum analysis (RSA) is mostly preferred instead of the THA. However, The THA is a more trustworthy analysis method to assess the system dynamic response while others provide just approximate-solution.

Assuming that all structural members perform in the elastic range, and all nonlinearity, including materials or geometric, are not considered for THA analysis. The Benchmark building, including or not CFs placements as a linear time-invariant (LTI) system, is modeled as a state-space method employed in Simulink to compute structural responses easily. The analytical models need to be accurately constructed and coded in the structural analytical program package to perform structural responses in the THA for the structure with or without the different CFs placements. Therefore, the THA simulations were performed in Matlab & Simulink [31] in this study, and the results for each case were obtained and saved for evaluation purposes.

2.5. Ground Motion Selections

There are a lot of strong earthquakes that have been occurred in the last century. The performance of the energy dissipating system like cross bracing frames mostly depends upon the earthquake input characteristics. Therefore, in this study, three bidirectional historical earthquakes represent typical x-dominant, y-dominant, and both are determined to test the energy dissipating system, see Figure 5a, Figure 5b, and Figure 5c.
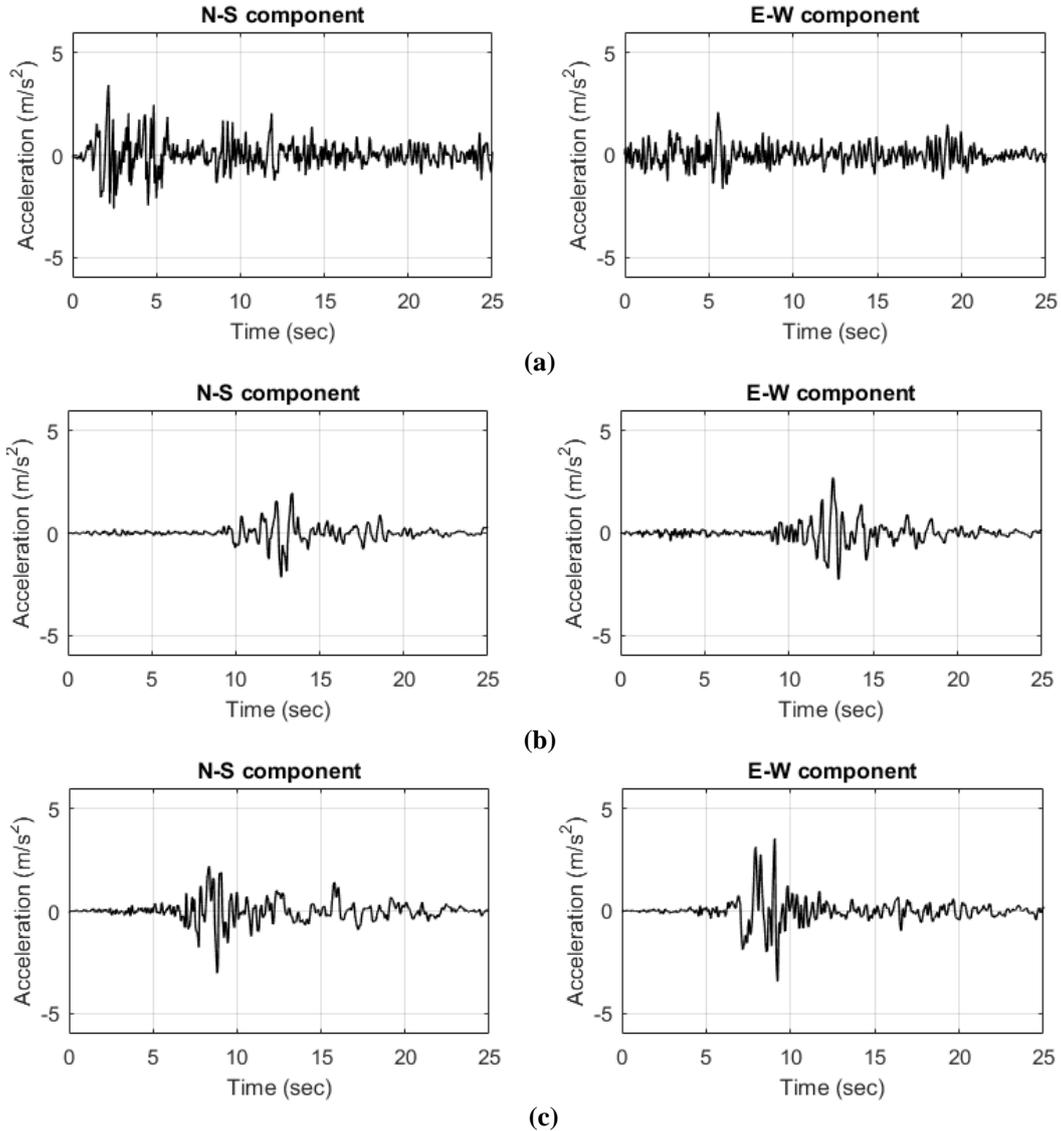
Figure 5. Three bidirectional historical real-life earthquakes: **(a)** El Centro, **(b)** Loma Prieta, and **(c)** Kocaeli earthquake

3. Results and Discussion

Benchmark 9-story steel structure is acquired as a reference structure, and the time history analyses are made by retrofitting the structure with three different CFs placements. The fundamental modal frequencies for all model structures are obtained and given in Table 4. As understood from it, whereas the contribution of the CFs placement into the lateral bearing system of the Benchmark building increases overall of the natural frequencies, for instance, the first mode is increased by 12% (from 7.71 to 8.69), which generally dominates total response of the structures, see Table 4. Moreover, it increases the load capacity in the lateral and torsional directions. As looking into CFs placements (Case 1; Case 2; and case 3), they all have a slightly different modal frequency in the lateral directions (x- and y-) thanks to HSS selection of the bracing elements. It improves the lateral loading capacity equally in the x- and y- direction; however, the building with Case 3 placement is more restricted against torsional motions. This fact can occur that the CFs placement in Case 3 can eliminate the eccentricity between CM and CS successfully compared to other placements and the bare structure. Therefore, Case 3 has the minimum modal frequency (26.26 rad/s) in the torsional direction.

Table 3. Calculated eccentricities in both orthogonal directions for the bare Benchmark building,
Case 1, Case 2, and Case 3

The bare Benchmark		Case 1		Case 2		Case 3	
e_x (m)	e_y (m)	e_x (m)	e_y (m)	e_x (m)	e_y (m)	e_x (m)	e_y (m)
6.63	1.76	4.21	-2.58	2.53	-2.58	3.37	-1.01
3.53	1.23	2.58	-1.76	1.34	-1.76	1.96	-0.58
7.67	3.07	6.12	0.12	5.20	0.12	5.66	1.00
6.18	2.38	4.84	-0.52	3.86	-0.52	4.35	0.44
3.32	1.19	2.52	-1.52	1.42	-1.52	1.97	-0.45
2.16	0.75	1.60	-1.92	0.42	-1.92	1.01	-0.77
1.75	0.80	1.27	-1.64	0.01	-1.64	0.64	-0.60
1.58	0.79	1.09	-1.73	-0.31	-1.73	0.39	-0.65
1.21	0.73	0.92	-1.11	-0.20	-1.11	0.36	-0.31

Most of the structure in the real-life is likely to undergo unequally-distributed-eccentricity for each level because of the unequal distribution of structural components like columns, beams, and so on, and material and ground motion uncertainties. With consideration of these facts, three-historical earthquake ground motions are selected, and the size of used cross frames (HSS section) is assigned according to the fact that shear force is decreasing with the height of the structure. The cross frames are only integrated into moment-resisting frames of the Benchmark building, as seen in Figure 4. For all cases (case 1, case 2, and case 3), the eccentricity calculation is made, including the contribution of the simple frames. As seen in Table 3, the eccentricity is not the same throughout structure height. Each floor has a different eccentricity by comparing to one another. The inclusion of cross-frame placements changes the eccentricity location sometimes in the left-hand side and right-hand side from the center of mass (CM). Therefore, some values are shown negative, and some are positive in Table 3, which indicates the relative eccentricity distance according to the CM.

Table 4. The fundamental modal properties of the model buildings

Modes (rad/s)	Dominant dir.	Benchmark build.	Cross frame placements		
			Case 1	Case 2	Case 3
1st mode	y lateral	7.71	8.69	8.69	8.69
2nd mode	x lateral	12.87	13.42	13.42	13.43
3rd mode	y lateral	20.88	23.55	23.55	23.55
4th mode	Θ torsional	26.19	26.28	26.29	26.26
5th mode	x lateral	33.25	34.84	34.84	34.86

After time history analyses are made under three selected real saved earthquake ground motions, the peak responses of the placements of the CFs placements compared with one another, including the bare Benchmark building. The results show that all three cross-frame installations are substantially surpassed the lateral vibrations, and there are slight differences for the peak response of the cross-frame placements. However, for torsional vibration control, only Case 3 is significantly reduced for both tuning and detuning loading scenarios, see Table 5. In the case of the El Centro earthquake, Case 1 (0.132) and Case 2 (0.130) placements even increase the torsional effects in comparison with the bare structure. Moreover, Case 3 gives the best performance with the values (0.08 (32% decrease); 0.071(50% decrease); and 0.133 (31% decrease) for the response reduction in the torsional direction for all earthquake loading cases, besides, the response reduction in the lateral directions.

Table 5. The maximum response of the case structures under bidirectional loadings, units; cm and 10^{-3} rad

Structure	El Centro Peak response			Loma Prieta Peak response			Kocaeli Peak response		
	x-	y-	θ-	x-	y-	θ-	x-	y-	θ-
Bare Benchmark	8.24	10.65	0.11	4.38	17.10	0.14	6.29	13.18	0.19
Case 1	6.85	7.46	0.13	3.67	16.82	0.12	5.80	10.37	0.16
Case 2	6.85	7.46	0.13	3.66	16.85	0.08	5.81	10.39	0.14
Case 3	6.87	7.45	0.08	3.67	16.85	0.07	5.82	10.39	0.13

Overall, the CFs placement of Case 3 is so effective, especially in controlling torsional response as compared to other as well as in the lateral directions by significantly eliminating the eccentricity in the plan configuration.

4. Conclusion

Unlike using sophisticated modern control systems, the traditional energy dissipating devices with the right engineering design perspective can be useful as much as the modern control systems. Therefore, this study aims to observe and test the effects of CFs placements when the retrofitted structure is exposed to bidirectional three historical ground motions that might cause either tuning or detuning effects. The conclusions stated below can be figured out from the time history analysis results:

1. The contribution of the CFs placement into the moment resisting frames of the Benchmark building increases overall of the natural frequencies, for instance, the first mode is increased by 12% for all three loading cases, which generally dominates the total response of the structures.
2. The inclusion of cross frames struts into the moment frame in a structure has significant effects on the structural dynamics and stability. When they are integrated into the bare Benchmark building, it changes the eccentricity between the center of mass and stiffness for each floor significantly by increasing the structural lateral and torsional loading capacity effectively. Using them in the design of the structure with no torsional irregularity is not always the right way to follow because it may lead to unevenly distributed stiffness in the plan and elevation. Therefore, it can be convenient to have an engineering investigation on the system dynamic and stability, including additional energy dissipating systems before applying them.
3. All three cross-frame placements are successfully surpassed the lateral vibrations and slightly different for the peak response of the cross frame placements. However, only Case 3 is significantly reduced for both tuning El Centro (32% decrease) and detuning Loma Prieta (50% decrease), and Kocaeli (31% decrease) for torsional vibration control.
4. Overall, the CFs placement of Case 3 is a right engineering design perspective that is so effective, especially in controlling torsional response as compared to others as well as in the lateral directions by significantly eliminating the eccentricity in the plan configuration.

Author's Contributions

Corresponding author, OA, has performed and conducted on all stages of this research; the novelty of the research idea, theory, and its application, simulation and results, writing stage, and so forth.

Statement of Conflicts of Interest

The author declared no potential conflicts of interest for the research, authorship, and/or publication of this article.

Statement of Research and Publication Ethics

It is declared that the author has obeyed the rule(s) of the Research/Publication Ethics.

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