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Prevention of torsional irregularity in steel structures via brace members

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Abstract

Steel structures can be designed using moment-resisting frame systems or braced frame systems. Torsional irregularities can occur in non-symmetrical structures designed with moment-resisting steel frame systems. These torsional irregularities can be eliminated by adding braces to moment-resisting steel frame systems. In this study, X-type braces were added to the moment-resisting steel frame system with A1 torsional irregularity and torsional irregularity was prevented.

Introduction

The use of steel in high-rise buildings and industrial structures has been increasing recently with the development of construction technology. Especially, having a high modulus of elasticity makes it superior to other structural materials. Steel structures show ductile behaviour under horizontal loads such as winds and earthquakes. In addition, they have high energy absorption capacity [1], [2]. Therefore, steel structures are mostly preferred especially in earthquake zones.

Moreover, steel structures can be designed as special moment-resisting framed systems (SMF), special concentrically braced framed systems (SCBF), and eccentrically braced framed systems (EBF) [3]. Steel braced frame systems are increased in horizontal load carrying capacity, however restrict the lateral displacement considerably. The cross-section, direction, geometry and location of the used brace member enormously affect the behavior of the structure [4].

In non-symmetrical structure designed as SMF can be occured torsional irregularity. In the design of the steel structures in our country, the torsional irregularity of the non-symmetrical structures must be checked according to the Turkish Building Earthquake Code-2018 (TBEC-2018). This irregularity can be avoided by adding concentrically and eccentrically steel braces to the structure designed as SMF. Besides, torsional irregularity can be occured not only in non-symmetrical structures designed as SMF, but also symmetrical structures because of the strength differences and location of the using braces [5].

In this study, a five-storey non-symmetrical steel structure with A1 type torsional irregularity according to TBEC-2018 was examined. The principle aim of the study is to prevent torsional irregularity by adding X-type concentrically steel braces to this structure.

Material and Method

In this study, five-storey non-symmetrical steel frame structure with 6 m span was examined. Each floor height of the structure was equal and 4.5 m. The structure coordinates was 37.97986°-32.593169° and soil class is ZD. Structural analysis was performed via SAP2000 in order to acquire structural weight and horizontal displacements. According to structural analyses results, cross-section of the beams and columns was determined. Then, concentrically steel braces were added to the structure and the analysis were repeated in order to indicate the effect of steel braces. The structure was designed as to be utilized be used as a industrial building. The view of the examined structure are shown in Figure 1.

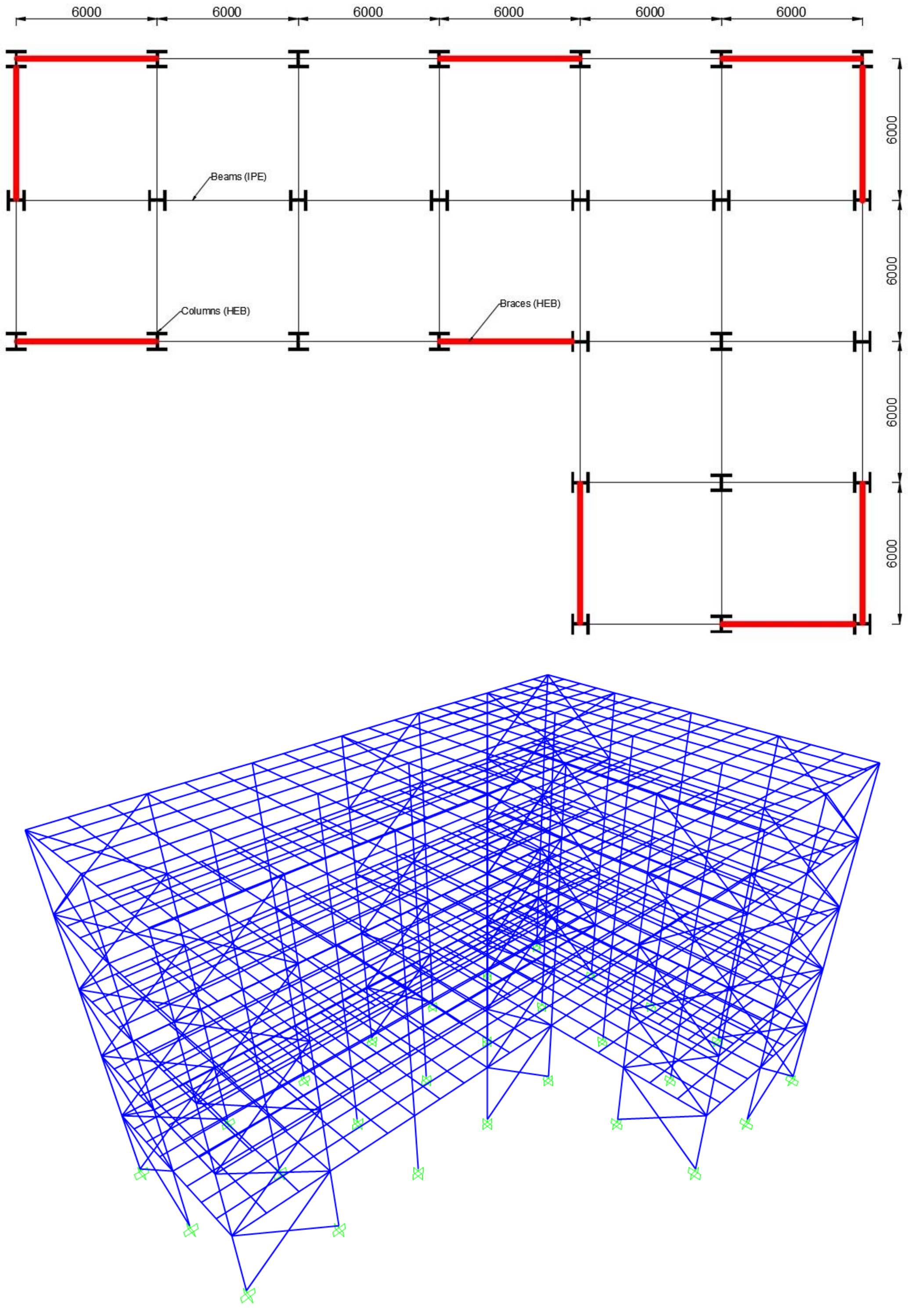

Figure 1. Examined Structure (3D and x-y views)

In the structural analyses, the snow and wind load values were implemented from the Turkish Standards (TS). The calculation details of snow load was taken from Effects on Structures-Part 1-3 (TS EN 1991-1-3) and the wind load was taken from Effects on Structures-Part 1-4 (TS EN 1991- 1-4). Vertical loads (dead load, roof live load, live load, snow load) acted on the structure were defined in the direction of gravity in SAP2000 modelling. The vertical load values calculated are given in Table 1. Wind loads were affected on both in SAP2000. The terrain category, orographic coefficient, turbulence coefficient, structural coefficient and air density values for the mentioned coordinates through the rigid diaphragms were specified for calculation of the wind loads.

Table 1. Vertical load values

Roof Slab (kN/m²)	
G (dead load)	4
Qr (roof live load)	2
S (snow load)	1,155
Slab (kN/m²)	
G (dead load)	10
Q (live load)	5

Horizontal and vertical earthquake effects were also considered in the structural analysis. The earthquake parameters for the mentioned coordinates were taken from Turkey Earthquake Hazard Maps Interactive Web Application. The information taken was given in Table 2 for Earthquake Ground Motion Levels 2 and 3 (EGML-2, EGML-3).

Table 2. Earthquake parameters

Earthquake Ground Motion Levels	Soil Class	S_S	S_1	PGA [g]	PGV [cm/sn]	T_A (sn)	T_B (sn)	T_L (sn)	S_{DS}	S_{D1}
EGML-2	ZD	0,294	0,070	0,127	6,444	0,073	0,365	6	0,460	0,168
EGML-3	ZD	0,095	0,026	0,042	2,392	0,082	0,411	6	0,152	0,062

The vertical earthquake effect was calculated with the Equation 1 given below in accordance with TBEC-2018 4.4.3.2 and the dead load was added as G.

$$E_d{}^{(Z)} \approx (2/3) S_{DS}\, G \quad (1)$$

The load combinations used in the structural analyses were determined according to Design, Calculation and Constructional Principles of Steel Structures-2018 (DCCPSS-2018) Section 5.3.1 Load and Resistance Factor Design (LRFD) and TBEC-2018 Section 4.4.4. Wind (W) loads were taken into account on both x- and y- directions, while earthquake loads (E) were taken into account on the x- y- and z- directions. In addition, according to TBEC-2018 4.4.4.2 (a), factorized 1.2G is used instead of G in TBEC-2018 Equation 4.11. The load combinations (C) to be used in the examined structure were listed below.

C1 : 1.4G
C2 : 1.2G+1.6Qr
C3 : 1.2G+1.6S
C4 : 1.2G+1.6Q+0.5Qr
C5 : 1.2G+1.6Q+0.5S
C6 : 1.2G+1.6Qr+1.0Q
C7 : 1.2G+1.6S+1.0Q
C8 : 1.2G+1.6Qr +0.8Wx
C9 : 1.2G+1.6Qr +0.8Wy
C10 : 1.2G+1.6S+0.8Wx
C11 : 1.2G+1.6S+0.8Wy
C12 : 1.2G+1.0Q+0.5Qr+1.6Wx
C13 : 1.2G+1.0Q+0.5Qr+1.6Wy
C14 : 1.2G+1.0Q+0.5S+1.6Wx
C15 : 1.2G+1.0Q+0.5S+1.6Wy
C16 : 1.2G+1.0Q+0.2S+1.0Ex
C17 : 1.2G+1.0Q+0.2S+1.0Ey
C18 : 0.9G+1.6Wx
C19 : 0.9G+1.6Wy
C20 : 0.9G+1.0Ex
C21 : 0.9G+1.0Ey
C22 : 1.2G+1.0Q+0.2S+1.0Ex+0.3Ey
C23 : 1.2G+1.0Q+0.2S+0.3Ex+1.0Ey

The steel class of the columns, beams, secondary-beams and braces used in the structures had been considered as S275. The cross-sections of columns and braces were selected among HEB profiles and the cross-sections of beams and secondary-beams were selected among IPE profiles. According to TBEC-2018 Table 4.1 C11, the structural system behaviour coefficient R=8 and the overstrength coefficient D=3 were selected for the SMF. Additionally, according to Table 4.1 C15, R=6 and D=2.5 were selected for the SCBF.

Results

At the end of the conducted structural analyses, according to DCCPSS-2018 and TBEC-2018, the minimum cross-sections of the structure were determined. The effective relative storey displacement in both directions (x-, y-) of the two structural models were checked according to TBEC-2018 Equation 4.34b and with recpect to the most dominant load combinations. Additionally, the torsional irregularities were investigated and they were checked according to TBEC-2018 Section 3.6 (load combinations C22-C23). The final results obtained from SAP2000 analyses were given in Table 3-4-5-6.

Table 3. Relative storey displacement (x- direction)

Frame	Floor	Height (mm)	$u_i^{(x)}$ (mm)	$\Delta_i^{(x)}$ (mm)	$\delta_i^{(x)} = \frac{R}{I}\Delta_i^{(x)}$ (mm)	$\lambda_i^{(x)} \frac{\delta_i^{(x)}}{h_i}$	$\lambda_i \leq 0.008$
SMF	1	4500	6,18	6,18	49,46	0,0040	✓
	2	4500	27,94	21,76	174,08	0,0142	X
	3	4500	64,43	36,49	291,94	0,0239	X
	4	4500	109,33	44,89	359,13	0,0294	X
	5	4500	158,47	49,15	393,17	0,0322	X
SCBF	1	4500	0,96	0,96	7,65	0,0006	✓
	2	4500	2,68	1,73	13,81	0,0011	✓
	3	4500	4,89	2,21	17,64	0,0014	✓
	4	4500	7,44	2,56	20,45	0,0017	✓
	5	4500	9,97	2,53	20,21	0,0017	✓

Table 4. Relative storey displacement (y- direction)

Frame	Floor	Height (mm)	$u_i^{(x)}$ (mm)	$\Delta_i^{(x)}$ (mm)	$\delta_i^{(x)} = \frac{R}{I}\Delta_i^{(x)}$ (mm)	$\lambda_i^{(x)} \frac{\delta_i^{(x)}}{h_i}$	$\lambda_i \leq 0.008$
SMF	1	4500	42,41	42,41	339,306	0,0278	X
	2	4500	174,59	132,18	1057,45	0,0867	X
	3	4500	380,24	205,65	1645,18	0,1349	X
	4	4500	624,68	244,44	1955,48	0,1603	X
	5	4500	887,52	262,84	2102,74	0,1724	X
SCBF	1	4500	3,44	3,44	27,49	0,0023	✓
	2	4500	8,59	5,15	41,19	0,0034	✓
	3	4500	14,44	5,85	46,83	0,0038	✓
	4	4500	20,61	6,18	49,40	0,0041	✓
	5	4500	26,28	5,66	45,29	0,0037	✓

Table 5. Torsional irregularities (x- direction)

Frame	Floor	Height (mm)	$(\Delta_i^{(x)})_{max}$ (mm)	$(\Delta_i^{(x)})_{min}$ (mm)	$(\Delta_i^{(x)})_{ort}$ (mm)	$\eta b_i^{(x)} = (\Delta_i^{(x)})_{max} / (\Delta_i^{(x)})_{ort}$	$\eta b_i^{(x)} > 1,2$
SMF	5	4500	18,6	3,30	10,95	1,70	X
	4	4500	13,4	3,20	8,30	1,61	X
	3	4500	8,50	2,80	5,65	1,50	X
	2	4500	4,20	1,20	2,70	1,56	X
	1	4500	1,10	0,70	0,90	1,22	X
SCBF	5	4500	1,30	1,00	5,65	0,23	✓
	4	4500	9,50	7,40	8,45	1,12	✓
	3	4500	6,10	4,90	5,50	1,11	✓
	2	4500	3,30	2,70	3,00	1,10	✓
	1	4500	1,10	1,00	1,05	1,05	✓

Table 6. Torsional irregularities (y- direction)

Frame	Floor	Height (mm)	$(\Delta_i^{(y)})_{max}$ (mm)	$(\Delta_i^{(y)})_{min}$ (mm)	$(\Delta_i^{(y)})_{ort}$ (mm)	$\eta b_i^{(y)} = (\Delta_i^{(y)})_{max} / (\Delta_i^{(y)})_{ort}$	$\eta b_i^{(y)} > 1,2$
SMF	5	4500	52,70	11,40	32,05	1,64	X
	4	4500	36,30	9,10	22,70	1,60	X
	3	4500	21,50	6,60	14,05	1,53	X
	2	4500	9,50	3,80	6,65	1,43	X
	1	4500	2,20	1,10	1,65	1,33	X
SCBF	5	4500	12,10	11,60	11,85	1,02	✓
	4	4500	9,20	8,70	8,95	1,03	✓
	3	4500	6,20	5,70	5,95	1,04	✓
	2	4500	3,50	3,10	3,30	1,06	✓
	1	4500	1,30	1,10	1,20	1,08	✓

From these obtained results, the structure designed as SMF does not satisfy the relative storey displacement condition in both directions. Besides, while the horizontal displacement of the structure designed as SMF was approximately 158 mm in the x-direction, it decreased approximately 10 mm in the structure model designed as SCBF with SCBF. Likewise, it decreased from about 887 mm to about 26 mm in the y-direction. The structures designed as SMF and SCBF were examined in terms of the A1 torsional irregularities. It was shown that the structure designed as SMF did not provide the condition of torsional irregularities, while the structure designed as SCBF satisfied it. Accordingly, the torsional irregularities can be eliminated by adding braces to the non-symmetrical structures designed as SMF.

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