Mathematical and Computational Applications, Vol. 18, No. 3, pp. 438-447, 2013

NOVEL BRACING TYPE AGAINST SEISMIC LOADING: KX TYPE

M. Akif Kutuk and Ibrahim Gov

Department of Mechanical Engineering, University of Gaziantep, 27310, Gaziantep, Turkiye
kutuk@gantep.edu.tr

Abstract- In this study, a new bracing system is proposed which is named as KX type. Element removal method is used to obtain this new bracing. KX type optimized bracing is compared with V, and K type bracings under seismic loading. Maximum deformation value is used as performance indicator to compare effectiveness of V, K, and proposed KX type bracings to resist seismic loads. The proposed KX type bracing, yielded 99.72%, 93% and 88% reduced deformation with respect to unbraced, K type, and V type bracings respectively.

Key Words- Topology optimization, Seismic analysis, Bracing design.

1. INTRODUCTION

During earthquakes buildings which are not designed and/or constructed properly cause many casualties. These kinds of buildings can be rehabilitated with the use of different systems. One of these methods is to use extra structural elements like walls or bracings. Strengthening the existing columns with extra concrete or steel jackets may be another alternative. Between these two alternatives, steel bracings are generally preferred due to high strength/weight ratio and ease of application. Hence with the use of steel bracings, seismic performance of a weak building can be increased to resist an earthquake.

The shape and topology optimization of continuum structures has been an active research area for a few decades [1, 2]. Maheri *et al.* [3] studied pushover loads experimentally on scaled model of ductile reinforced concrete (RC) frames directly braced by steel X and knee braces. They stated that when designing or retrofitting for a collapse-level earthquake, knee bracing is a more effective system. Youssef *et al.* [4] evaluated the efficiency of RC frames experimentally. They applied two cyclic loading tests on a moment frame and a braced frame. Test results showed that the braced frame resisted higher lateral loads than the moment frame and provided adequate ductility.

Generally, used bracing systems are grouped into two categories namely concentric and eccentric bracings. Some of them are shown in Figure 1.

Ghobarah and Abou-Elfath [6] investigated the seismic performance of low-rise non-ductile reinforced concrete buildings rehabilitated by using eccentric and concentric steel bracing. Compared to the behavior of the concentric bracing case, eccentric bracing cases exhibited lower deformation and damage when subjected to earthquake ground motions.

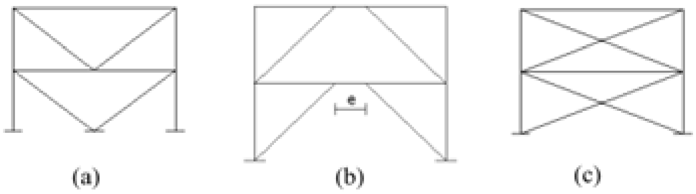


Figure 1. Different types of concentric steel bracing systems (a) V-bracing, (b) K-bracing, and (c) X-bracing [4, 5, and 6].

2. DESIGN OF BRACING

2.1. Topology optimization

In the design stage, the designer may use two methods, one of them is trial & error method and the other one is computer aided design (CAD). Trial & error method is a conventional method and it is commonly used for determining the appropriate bracing type among the alternatives. X, V, or K bracing types are commonly used. Firstly, these types of bracing are applied to building. Then, these braced buildings are analyzed and the best one is taken as the optimum brace for minimum deformation. In this approach the designer is limited to initially decided bracing set and the best one in this set is determined as the solution.

On the other hand, CAD methods are used very commonly in industrial applications, especially to design new products. The designed product can be improved easily applying the structural analysis. Hence the design time and costs are decreased. Structural optimization methods are developed as a step to reach the optimum design, and topology optimization method is one of these structural optimization methods.

Topology optimization has become popular and has been successfully applied into industrial design since 1988, when Bendsoe and Kikuchi [7] introduced the microstructure/homogenization approach for topology optimization. In the last decades, many methods have been developed to facilitate and make the topology optimization useful. Some mostly used methods are Material Distribution Method (density method), Level Set Approach (LSA), Homogenization Method (HM), Optimality Criteria Method (OCM), Element Removal Method (ERM), and etc.

By using topology optimization, optimum bracing configuration can be obtained for buildings. Determination and use of optimum bracing will yield extra strength to the building with minimum material usage compared to bracing determined by trial & error method. In the proposed method, a new bracing type is obtained by using ERM and the effect of the bracing on deformation is compared with that of traditional bracing types.

2.2. Element Removal Method (ERM)

The main idea of the topology optimization is removal of inefficient (comparatively small stressed) elements from the design domain. The idea is directly applied in the ERM optimization process. For selection of the elements to be removed, stress values are considered to be the significant factor. FEA is applied on the design domain and after each FEA operation, elements with the lowest stress values are removed from the design space. By using this concept, a new element removal algorithm [8] is developed for statically loaded parts. This recently developed element removal method is adapted to fatigue loading conditions. Algorithm of the method is given in Figure 2. The given algorithm is also modified to be used with seismic loadings.

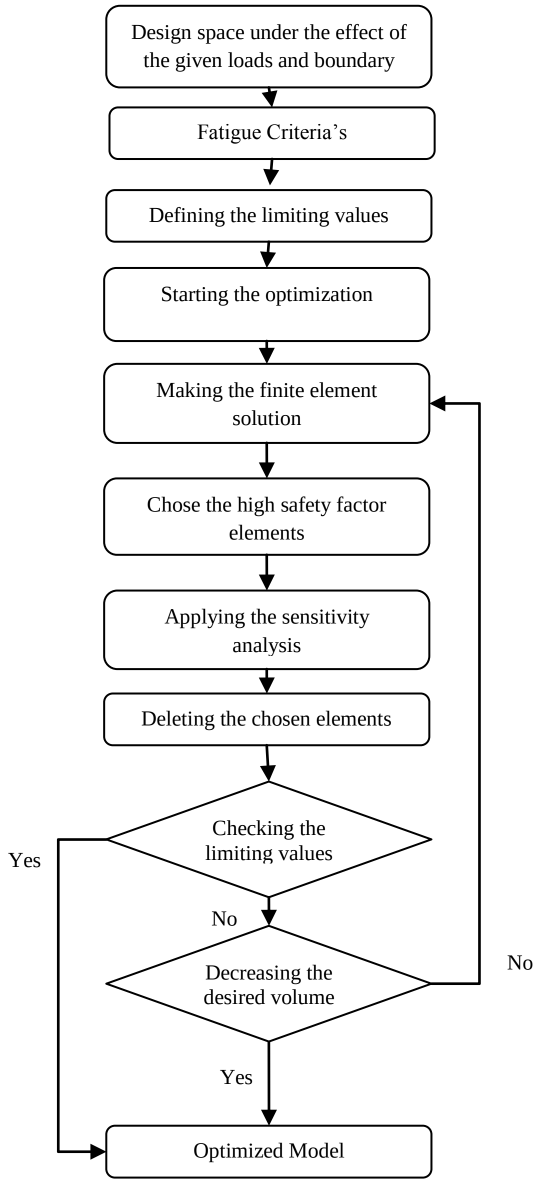


Figure 2. Algorithm for applying topology optimization under fatigue loading

During the optimization process, number of elements with high factor of safety will be deleted and hence next design space will be obtained. This process is a cyclical process. After this optimization cycle, the optimized model in Figure 3 will be converted into the geometry in Figure 4.

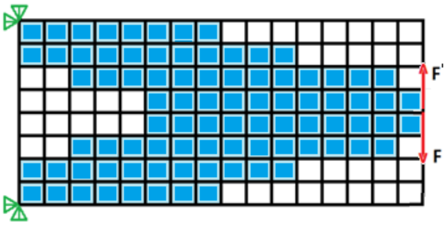


Figure 3. Optimized model before element remove

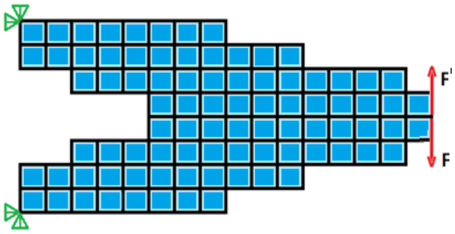


Figure 4. Optimized model after element remove

2.3. Optimum bracing geometry by ERM

An unbraced frame is modeled with one bay and two-story as shown in Figure 5. Dimension of the building is modeled as 6m in width and 6m in total height. The design domain is placed in the second floor of the building as shown in Figure 6. The framework of the steel building is fixed at points A and B. All beams and columns have rectangular cross-section with 0.05 m width and 0.15 m height. For the bracing, plane element is used with 0.05 m thickness. Material is defined as linear-elastic ss41 steel plate [9] (Young's modulus, E=200 GPa, density ρ=7800 kg/m^3, and yield strength, S_y=235Mpa) for all members. Ansys BEAM4 and PLANE82 elements are used for mesh of the structure. Time history analysis is performed to obtain response of the whole structure. At the design domain, 1440 N/m floor load is applied at the top of the structure and negative & positive acceleration is applied to simulate a seismic loading.

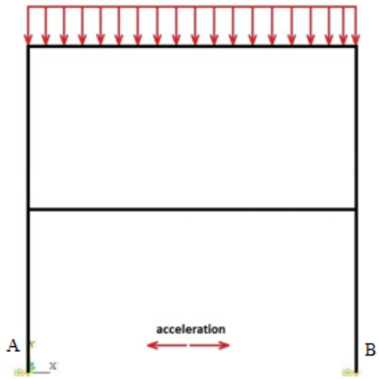


Figure 5. Unbraced frame with one bay and two-story

Design domain is optimized under the effect of seismic loading conditions. This loading condition is applied on the model hence developed element removal algorithm is used for the optimization process. Volume reduction ratio of 70% is taken as the design constraint. Some steps of the optimization are given in Figure 7 up-to reach of final reduction ratio. Optimized domain is obtained as shown in Figure 8.

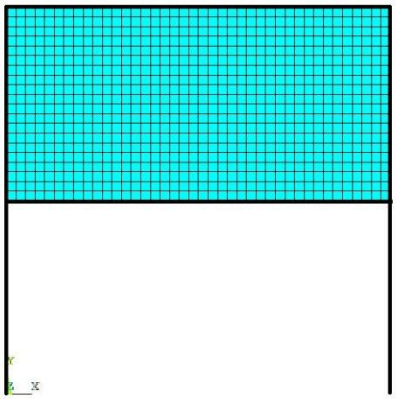
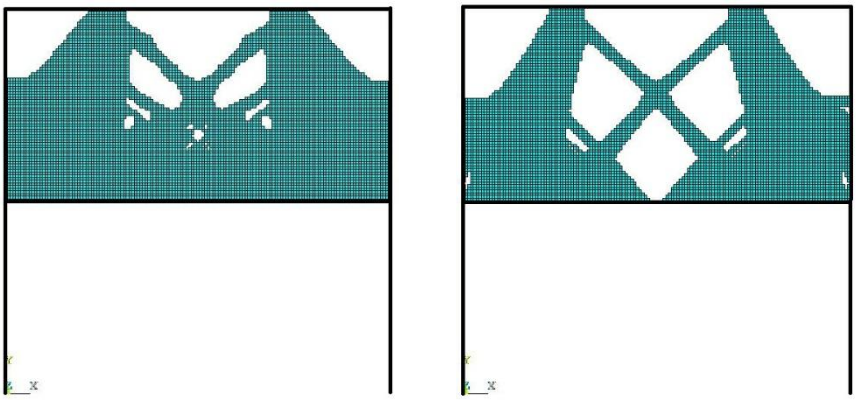


Figure 6. Design domain with one bay and two-story



a. Volume reduction ratio of 20% b. Volume reduction ratio of 40%

Figure 7. Steps of Optimization

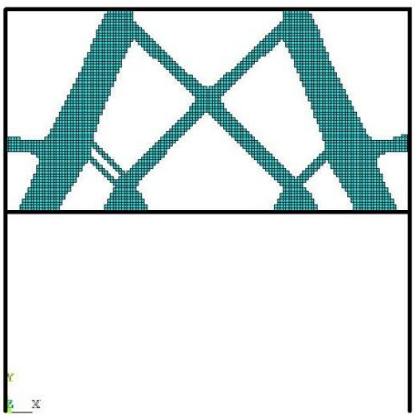


Figure 8. Optimized domain, volume reduction ratio of 70%

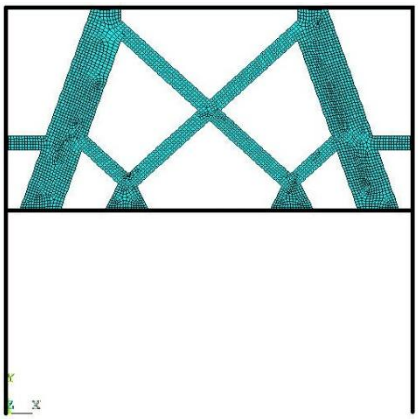


Figure 9. Remodeled optimized bracing

Topology optimization gives initial idea for the design space. Considering this fact, the outcome of the optimization is generally modified to ease the operation or the production. Hence optimization result of Figure 8 can be remodeled to obtain the final design as shown in Figure 9. Optimized bracing, shown in Figure 9 is different from commonly used bracing types. The final shape of the optimization is named as **KX type** bracing.

3. PERFORMANCE OF BRACINGS

ANSeismic [10] Matlab code is used to simulate the seismic load shown in Figure 10. By using this code, earthquake data can be converted into Ansys acceleration data as in Figure 11. To see the seismic performance of the proposed KX type bracing, the deformation results of optimized KX type bracing (Figure 12) and generally used bracings (V, and K type as shown in Figures 13-14) are compared. For all three types of bracings, element numbers used in finite element analysis are taken about 7700.

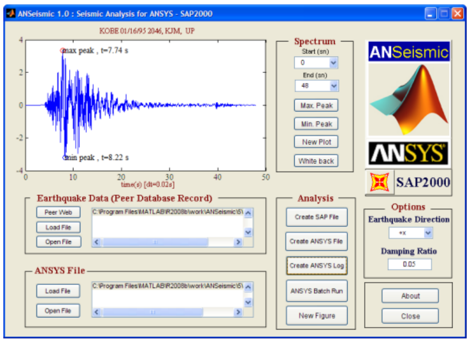


Figure 10. ANSeismic Program main window [10]

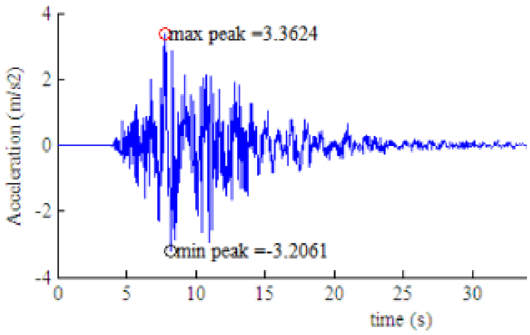


Figure 11. KJM-UP component of 1995 Kobe Earthquake (KJMA Station) [10]

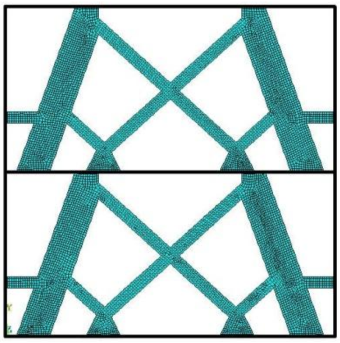


Figure 12. Optimized braced frame for seismic loading

In this study, 1995 KOBE Earthquake data [10] given in Figure 11 is used as seismic loading.

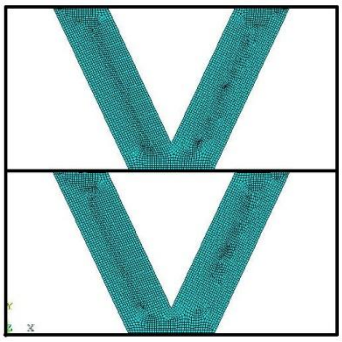


Figure 13. V-braced frame for seismic loading

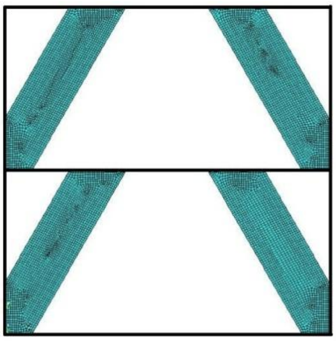


Figure 14. K-braced frame for seismic loading

Table 1. Deformation (δ) results of bracing systems for time interval 7.50 and 8.50 sec.

Time (sec)	**Acceleration (m/s^2)**	**Without bracing δ (mm)**	**V type δ (mm)**	**K type δ (mm)**	**KX type δ (mm)**
7.50	1.2678	-10.9732	-0.1551	-0.1909	-0.0120
7.54	-0.7691	-15.7910	0.0982	0.1716	0.0068
7.58	0.5109	-4.6430	-0.0303	-0.1200	-0.0040
7.62	1.0385	9.2071	-0.1306	-0.1003	-0.0087
7.66	-0.2353	13.9379	0.1080	0.0350	0.0026
7.70	1.5685	4.6465	-0.1824	-0.1728	-0.0142
7.74	**3.3624**	**-10.9207**	**-0.2045**	**-0.4090**	**-0.0304**
7.78	2.0152	**-22.3188**	-0.1110	-0.2408	-0.0177
7.82	1.7965	-16.2627	-0.1941	-0.1623	-0.0153
7.86	2.7954	0.8781	-0.0999	-0.3735	-0.0241
7.90	1.6426	13.0585	-0.1889	-0.1723	-0.0142
7.94	0.1756	9.9822	0.0098	-0.0165	-0.0019
7.98	-1.0808	-2.4752	0.1216	0.1186	0.0091
8.02	-1.5170	-10.9228	0.0067	0.1882	0.0130
8.06	-1.0899	-6.8373	0.1829	0.1255	0.0097
8.10	-0.7109	5.7719	-0.0182	0.0717	0.0067
8.14	-0.9884	14.0022	0.0573	0.1126	0.0089
8.18	-2.3057	11.7113	0.2309	0.2533	0.0201
8.22	**-3.2061**	**2.0402**	**0.1205**	**0.4064**	**0.0279**
8.26	-1.2945	-3.7486	0.1867	0.1553	0.0112
8.30	2.6228	-4.9079	-0.2298	-0.3248	-0.0234
8.34	2.1120	-4.4550	-0.1652	-0.2618	-0.0178
8.38	0.6007	-4.2185	0.0108	-0.0736	-0.0049
8.42	-1.1931	-0.4286	0.0205	0.1610	0.0102
8.46	-2.8674	5.3348	**0.2499**	0.3118	0.0249
8.50	-2.1236	11.2114	0.1356	0.3052	0.0184

Deformation (δ) values for the considered models are tabulated in Table 1 under the effect of seismic loading for 7.50-8.50 sec. interval. The given period includes peak values of acceleration and deformations. Variations of deformation for different bracing types are plotted in Figure 15.

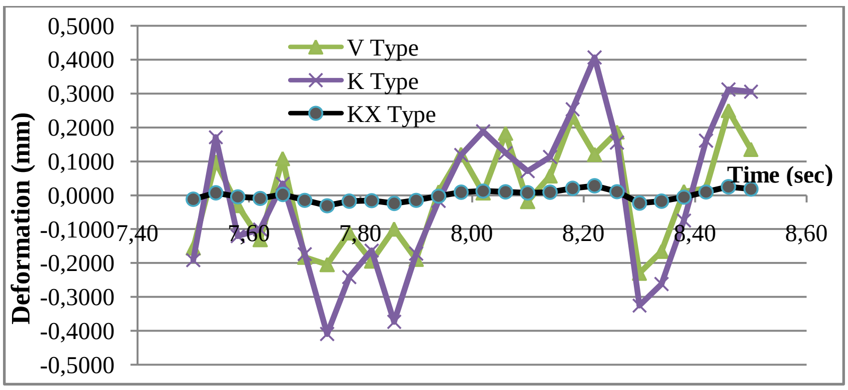
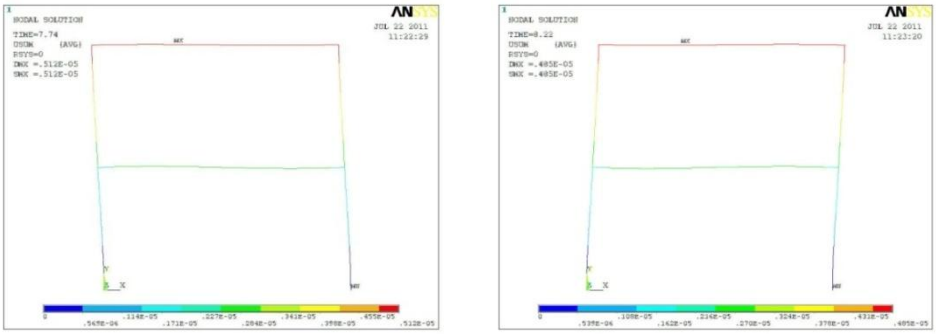


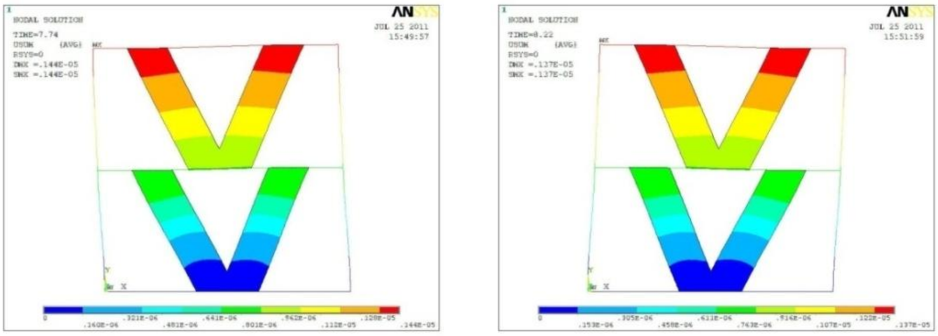
Figure 15. Effects of Different Bracings on Deformation (δ)

Deformation results for 2 story are compared at maximum acceleration (3.3624 m/sec^2 at 7.74 sec.) and minimum acceleration (-3.2061 m/sec^2 at 8.22sec.) values. Deformed shapes of unbraced, V-braced, K-braced and KX-braced frames are plotted in Figures 16 to 19 respectively.



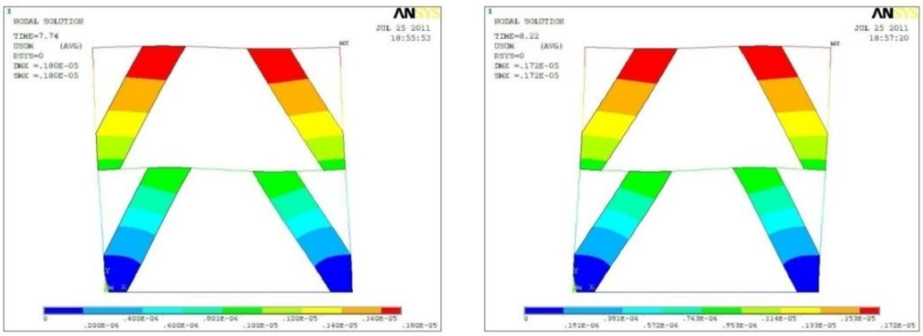
(a) at maximum acceleration (b) at minimum acceleration

Figure 16. Deformation results of unbraced frame



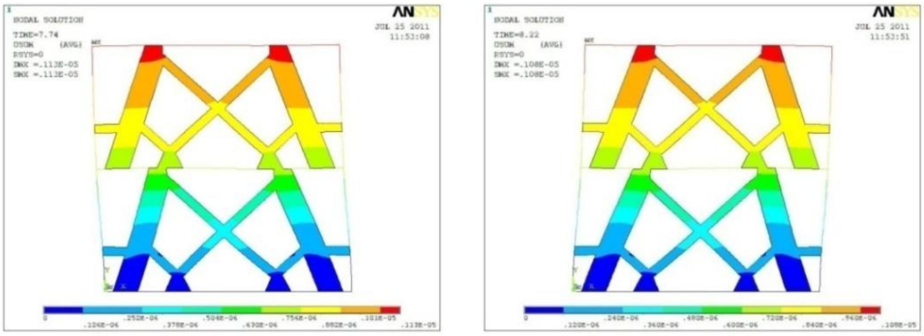
(a) at maximum acceleration (b) at minimum acceleration

Figure 17. Deformation result of V-braced frame



(a)at maximum acceleration (b) at minimum acceleration

Figure 18. Deformation result of K-braced frame



(a) at maximum acceleration (b) at minimum acceleration

Figure 19. Deformation result of opt. KX type braced frame

In Table 2, deformation results for unbraced, V braced, K braced, and optimized KX braced frames are given. Comparing the deformation values of V, and K type, V type yields better results. Furthermore, the optimized KX type yields minimum deformation of the structure under the effect of seismic load.

Table 2. Deformation (δ) results of bracings under the seismic analysis for 2-story

Bracing Model	**Deformation at 7.74 s**	**Deformation at 8.22 s**	**Reduction (%)**
Without bracing	11 mm	2 mm	-
V type	0.205 mm	0.121 mm	98.14
K type	0.409 mm	0.406 mm	96.28
KX type	0.031 mm	0.028 mm	99.72

Under the effect of maximum acceleration value at 7.74 sec., 0.409mm deformation is observed for K type bracing while V type is 50% better than K type with 0.205mm deformation. Comparing deformation values of V and KX type bracings; KX type yields 85% less deformation. Maximum von-Misses stress values induced in members due to seismic loading are given in Table 3 for 2-story models. In Table 4, deformation results for different story numbers are compared. In this comparison, K type is not given because of above reasons.

Table 3. Maximum von-Misses stress values of bracings under seismic loading

Bracing Model	**Stress at 7.74 s**	**Stress at 8.22 s**
V type	6.74 MPa	4.74 MPa
K type	16.10 MPa	15.6 MPa
KX type	1.70 MPa	1.57 MPa

Table 4. Deformation (δ) results of bracing systems under the seismic analysis

Bracing Model	**Deformation for 6 story**	**Deformation for 9 story**	**Deformation for 12 story**
V type	24.02 mm	32.75 mm	79.36 mm
KX type	4.35 mm	31.72 mm	32.09 mm

4. CONCLUSION

For improving the seismic performance of the structures, traditional bracing systems such as V or K types are generally used. In this study, a new bracing system namely KX type is obtained using topology optimization.

Previously developed ERM is improved for seismic loadings. Using the modified ERM, bracing is optimized under the effect of seismic loading. 1995 KOBE earthquake data is used as Ansys acceleration data. The acceleration data is applied to unbraced, optimized KX braced, V braced, and K braced structures. When the deformation results are compared, K braced frame is the weakest one. It provides 96.05% reduction in deformation; the V braced frame provides 98.14% reduction. The optimized KX braced frame is the most rigid frame and provides 99.72% reduction in deformation. Hence, using topology optimization, optimum bracing type is obtained. When comparing the stress results KX type is the most effective brace compared to V, and K type. Determination and use of optimum bracing will yield extra strength to the building compared to bracing determined by trial-error method.

Acknowledgement-The present research is funded by University of Gaziantep, Scientific Research Projects Funding Unit.

5. REFERENCES

1. R. T. Haftka and R. V. Gandhi, Structural shape optimization-a survey, *Computer Methods in Applied Mechanics and Engineering* **57,** 91-106, 1986.
2. K. Tawatchai and B. Sujin, Multi-objective topology optimization using evolutionary algorithms, *Engineering Optimization* **1**, 1–17, 2011.
3. M. R. Maheri, R. Kousari and M. Razazan, Pushover tests on steel X-braced and knee-braced RC frames, *Engineering Structures* **25**, 1697–1705, 2003.
4. M. A. Youssef, H. Ghaffarzadeh, and M. Nehdi, Seismic performance of RC frames with concentric internal steel bracing, *Engineering Structures* **29**, 1561–1568, 2007.
5. A. E. Ozel, Assessing effects of type and distribution of eccentric steel braces on seismic vulnerability of mid-rise reinforced concrete buildings, *M.Sc. Thesis in Civil Engineering*, University of Gaziantep, 2010.
6. A. Ghobarah and H. Abou-Elfath, Rehabilitation of a reinforced concrete frame using eccentric steel bracing, *Engineering Structures* **23**, 745–755, 2001.
7. M. P. Bendsøe and N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, *Computer Methods in Applied Mechanics and Engineering* **71**, 197-224, 1988.
8. I. Gov, Applying topology optimization to design of planer machine parts, *M.Sc. Thesis in Mechanical Engineering*, University of Gaziantep, 2009.
9. R. Tremblay, Inelastic seismic response of steel bracing members, *Journal of Constructional Steel Research* **58**, 665–701, 2002.
10. A. Sahin, ANSeismic – A Simple Assistant Computer Program for Implementing Earthquake Analysis of Structures with ANSYS and SAP2000, *International Conference on Advances in Civil Engineering,* Trivandrum, India, 9-14, 2010.