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Optimum bracing design under wind load by using topology optimization

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Abstract. Seismic and wind load performances of buildings are commonly improved by using bracing systems. In practice, standard bracing systems, such as X, Y, V, and K types are used. To determine the appropriate bracing type, the designer uses trial & error method among the standard bracings to obtain better results. However, using topology optimization yields more efficient bracing systems or new bracing can be developed depending on building and loading types. Determination of optimum bracing type for minimum deformation on a building under the effect of wind load is given in this study. A new bracing system is developed by using topology optimization. Element removal method is used to determine and remove the comparatively inefficient materials. Optimized bracing is compared with proposed bracing types available in the related literature. Maximum deformation value of building is used as performance indicator to compare effectiveness of different bracings to resist wind loads. The proposed bracing, yielded 99%, deformation reduction compared to the unbraced building.

Keywords: topology optimization; element removal; structural optimization; wind load; bracing

1. Introduction

Buildings which are not designed and/or constructed properly cause many casualties under wind load. These kinds of buildings can be rehabilitated with the use of different methods. 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 their high strength/weight ratio and ease of application. Hence with the use of steel bracings, wind performance of a building can be increased. Chan *et al*. (1995) presented an automatic resizing technique for the optimal design of tall steel building frameworks. They develop a computer-based method for the minimum weight design of lateral load-resisting steel frameworks. Mijar *et al*. (1998) applied a continuum structural topology optimization formulation to the concept design optimization of structural bracing systems that are needed to stiffen tall structures against side way under lateral-wind and seismic-type loading. Kareem *et al*. (1999) researched various techniques to reduce motions of tall buildings. The usage of active and passive damping devices in buildings is investigated. Also structural and

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aerodynamic designs are summarized which are used for improving wind and seismic performance of buildings. Liang *et al*. (2000) presented a performance-based optimization method for optimal topology design of bracing systems for multistory steel building frameworks with overall stiffness constraint under multiple lateral loading conditions. Material removal criteria are derived by undertaking a modification analysis on the mean compliance of a structure with respect to element removal. Abou-Elfath and Ghobarah (2000) investigated the seismic performance of low-rise non-ductile reinforced concrete buildings rehabilitated using concentric steel bracing. Ghobarah and Abou-Elfath (2001) examined the seismic performance of low-rise non-ductile reinforced concrete buildings rehabilitated using eccentric steel bracing. Maheri *et al*. (2003) studied experimentally pushover loads on scaled model of ductile RC frames directly braced by steel X and knee braces. Maheri and Akbari (2003) evaluated the seismic behavior factor for steel X-braced and knee-braced RC buildings. Ghaffarzadeh and Maheri (2006) developed a device that can release the compressive force in the bracing members and evaluate its performance. Youssef *et al*. (2007) experimentally evaluated the efficiency of braced RC frames. Mazza and Vulcano (2007) investigated the response of steel framed buildings by using viscoelastic or frictional dampers. Steel braces, damped braces, and combination of them in terms of human comfort are also compared. It is shown that, steel bracings provide more rigid frames in terms of displacements and accelerations. But, for human comfort damped bracings are proposed. Mazza and Vulcano (2011) inserted steel braces equipped with viscoelastic dampers (VEDs) ('dissipative braces') to improve the seismic or wind behavior of framed buildings. Then the earthquake and wind dynamic response of steel-framed buildings were compare with VEDs and achieve optimal properties of dampers and supporting braces. Maheri and Sahebi (1997) investigated the use of steel bracing in concrete-framed structures. They determined the degree of effectiveness of different diagonal bracing arrangements to increase the in-plane shear strength of the frame.

Generally, bracing systems are grouped into two categories namely concentric and eccentric bracings. Concentric types of bracing are opposite V-bracing, X-bracing, 2-story X-bracing, diagonal bracing, V-bracing, and K-bracing can be seen in the Fig. 1. Eccentric bracing are V-bracing, K-bracing, X-bracing, and Y-bracing as shown in Fig. 2.

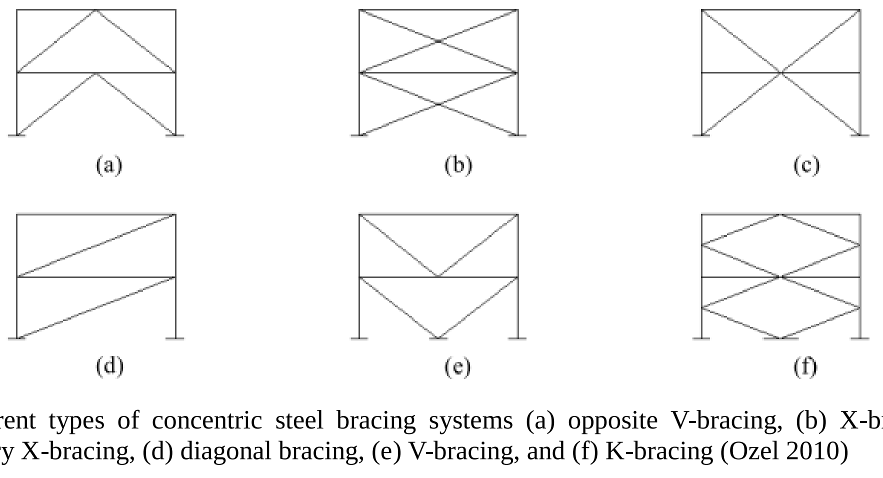


Fig. 1 Different types of concentric steel bracing systems (a) opposite V-bracing, (b) X-bracing, (c) 2-story X-bracing, (d) diagonal bracing, (e) V-bracing, and (f) K-bracing (Ozel 2010)

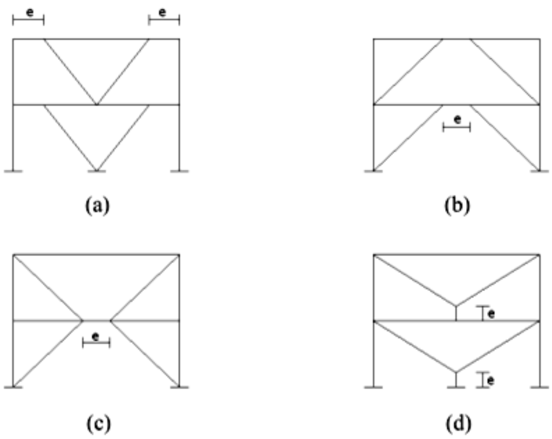


Fig. 2 Different types of eccentric steel bracing systems (a) V-bracing, (b) K-bracing, (c) X-bracing, and (d) Y-bracing (Ozel 2010)

A new configuration of steel braces is obtained to be considered for wind loads. The new configuration is obtained through a topology optimization procedure.

2. Design of bracing

2.1 Topology optimization

In the design stage of bracings, two methods are applied, one of them is trial &error method (Abou-Elfath and Ghobarah 2000, Abou-Elfath and Ghobarah 2001, Mazza and Vulcano 2011, Ozel 2010), and the other one is computer aided design (CAD) methods (Mijar *et al.* 1998, Liang *et al.* 2000, Hajirasouliha *et al.* 2011, Noilublao and Bureerat 2011). Trial& error method is a very old method and it is not commonly used. CAD methods are used very commonly in industrial application, especially to design a new product. The new product is designed on the computer, then structural analyses are used to examine if the product can endure load and boundary conditions. After the structural analysis, the designed product can be improved easily. Hence, the design duration and costs are reduced. Many methods are used for CAD; structural optimization is one of them. Structural optimization methods are developed for designers to obtain the optimum design in the shortest time. Topology optimization is a powerful structural optimization method to obtain initial design geometry.

To improve the strength of a building, designers select from commonly used bracings such as X, Y, V, or K type. By using topology optimization, appropriate bracing types can be obtained for different buildings. In this study, topology optimization is applied on a simple steel structure to minimize the deformation of the structure under wind load.

Topology optimization generates the optimal shape of a structure whatever the application of the structure is. The structural shape is generated within a pre-defined design space. In addition, the user provides structural supports and loads. Without any further decision and guidance of the user, the method will form the structural shape thus providing a first idea of an efficient geometry.

Therefore, topology optimization is a much more flexible design tool than classical structural shape optimization tools, where only a selected part of the boundary is varied. A given amount of structural mass is used to maximize a desired property of the structure. Usually maximized properties are stiffness or lowest eigenfrequency. Another useage of topology optimization may also be minimizing the amount of structural weight.

Topology optimization has become popular and has been successfully applied into industrial design since 1988 when Bendsoe and Kikuchi introduced the microstructure/homogenization approach for topology optimization. Bendsoe and Sigmund have systematically investigated new theories, methods and applications for topology optimization. In the last decades,many methods have been developed to facilitate and make topology optimization useful. Some mostly preferred methods are:

- Material Distribution Method (density method) (Cholaseuk 2006)
- Level Set Approach (LSA) (Yulin and Xiaoming 2004)
- Evolutionary Structural Optimization (ESO) (Tanskanen 2002)
- Material Cloud Method (MCM) (Chang and Youn 2006)
- Homogenization Method (HM) (Guest and Prevost 2006)
- Optimality Criteria Method (OCM) (Bendsoe and Sigmund 2002)
- Solid Isotropic Material with Penalization (SIMP) (Bendsoe and Sigmund 2002)
- Element Removal Method (ERM) (Gov 2009)

By using topology optimization, optimum bracing type 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 the related studies.

2.2 Element Removal Method (ERM)

The main idea of the topology optimization is the 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 (Gov 2009) is developed for statically loaded parts. The element removal method is compared by some other topology optimization methods and this comparison proved that ERM gives similar results but solution time can be decreased up to 90% by the method Gov (2009). Rapid and feasible results caused concentration on the method. This recently developed element removal method is adapted to fatigue loading conditions. Some steps are included to ERM considering fatigue load conditions which are fatigue criteria (infinite life or finite life, fatigue failure criteria's) and constraints (life, safety factors, etc.). Calculation of safety factor by using failure criteria is also included in the algorithm. Modification analysis is improved for fatigue conditions. Algorithm of the method is given in Fig. 3.

The question during optimization operation was "How many elements will be deleted at each loop?", that is decided by taking into account the total iteration number and the total volume reduction ratio. The amount of the elements to be deleted is about 2% of the initial domain. After each element removal operation, the rest of the elements are renamed to enumerate. Then these elements form the new design domain and the next optimization loop starts. These optimization cycles are stopped when one of the two criteria is true:

- volume reduction ratio
- pre-defined life or safety factor value is reached.

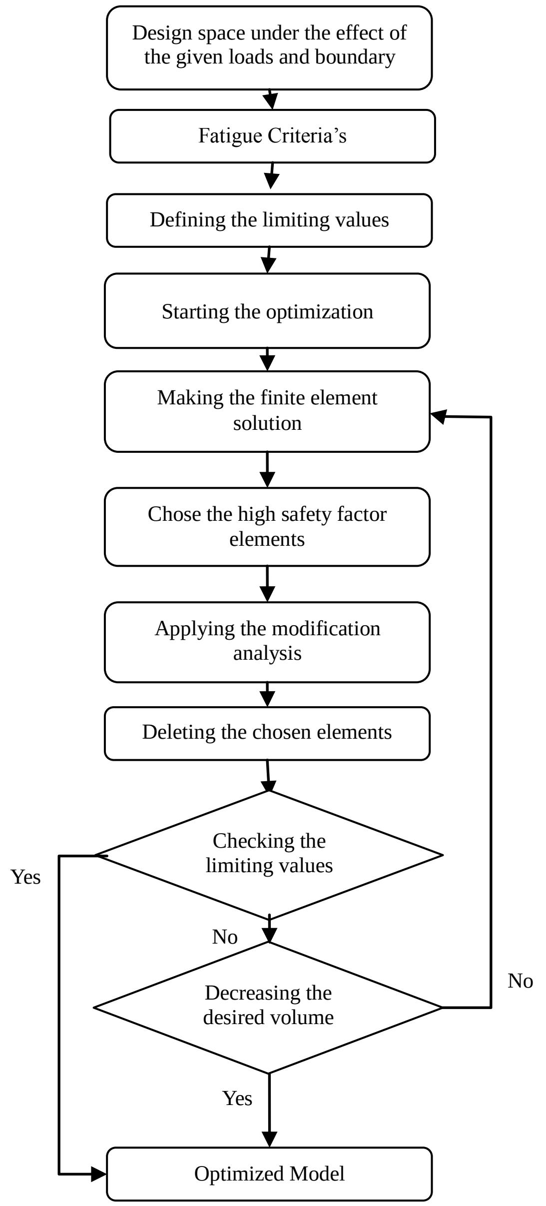


Fig. 3 Algorithm for applying topology optimization under fatigue loading

Steps of element removal method:

i. Firstly, draw the design domain with load and boundary conditions, then define the variables below:

Vr: volumetric reduction ratio,
Constraints: Safety factor (n_{all}) or life (N_{all})

Defining the life (infinite or finite):

- For infinite life calculations

$S_e = k_a k_b k_c k_d k_e k_f S_e'$ (General equation)

In this study, life is taken as infinite and *k* factor values are taken as unity. When calculating the safety factors of elements, Soderberg formula is used.

ii. After defining the variables, optimization loop can be initiated.

a. In the optimization loop, stress values of each element are obtained from FEA where ANSYS v12 package is used. Stresses are σ_{x1}, $\sigma_{x2,}$ σ_{y1}, σ_{y2}, σ_{xy1}, σ_{xy2} for two load cases. Alternating and mean stress values ***Sa*** and ***Sm*** are calculated for each element by using equations given below:

$$Sa_x = \frac{\sigma_{x2} - \sigma_{x1}}{2} \;;\quad Sa_y = \frac{\sigma_{y2} - \sigma_{y1}}{2} \;;\quad Sa_{xy} = \frac{\sigma_{xy2} - \sigma_{xy1}}{2}$$

$$Sm_x = \frac{\sigma_{x2} + \sigma_{x1}}{2} \;;\quad Sm_y = \frac{\sigma_{y2} + \sigma_{y1}}{2} \;;\quad Sm_{xy} = \frac{\sigma_{xy2} + \sigma_{xy1}}{2}$$

$$Sa = \sqrt{\left[(Sa_x)^2 + \left(Sa_y\right)^2\right] + 3\left(Sa_{xy}{}^2\right)}$$

$$Sm = \sqrt{\left[(Sm_x)^2 + \left(Sm_y\right)^2\right] + 3\left(Sm_{xy}{}^2\right)}$$

Calculating ***Sa*** and ***Sm***, safety factor ***n*** is calculated by using the equation given below for each element:

$$n = \frac{1}{\frac{Sa}{Se} + \frac{Sm}{Sy}}$$

b. Calculate how many elements will be removed from the design domain after every optimization loop:

$$Sn = Vr/In$$

where
Sn is the selected number of elements for removing and
In is number of optimization loops required.
c. Modification analysis:
Look at neighbours of selected element el_{ij};

$$el_{ij} = \{ \begin{matrix} 1 & if\ element\ exists \\ 0 & if\ \ no\ element \end{matrix}$$

	$el_{i(j-1)}$	
$el_{(i-1)j}$	el_{ij}	$el_{(i+1)j}$
	$el_{i(j+1)}$	

Fig. 4 Selected element el_{ij} and its neighbours

$$k_{ij} = el_{(i-1)j} + el_{i(j-1)} + el_{(i+1)j} + el_{i(j+1)}$$
$$n_{ij} = n_{ij} / k_{ij}$$
$$n = \mathrm{sort}(n)$$

where k_{ij} is weight factor for each element, and el_{ij} means that element exist or not at considered neighbourhood. Modification algorithm is used to obtain smooth boundary and to prevent checker-board element distribution.

d. Select elements from $n(1)$ to $n(\mathrm{Sn})$ which have high safety factor values (Comparatively less effective elements in the design domain).

e. Remove selected elements from the design domain.

f. Check for constraints:

If $n_{min} < n_{all}$ or $N_{min} < N_{all}$ then stop optimization loop

Else if reached the volume reduction ratio, stop optimization loop

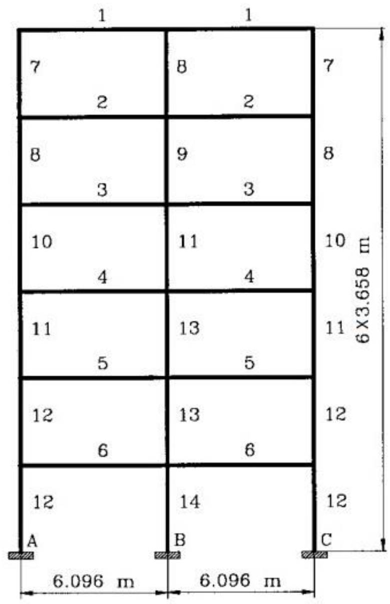
Else continue optimization loop

g. Finally take the optimized domain.

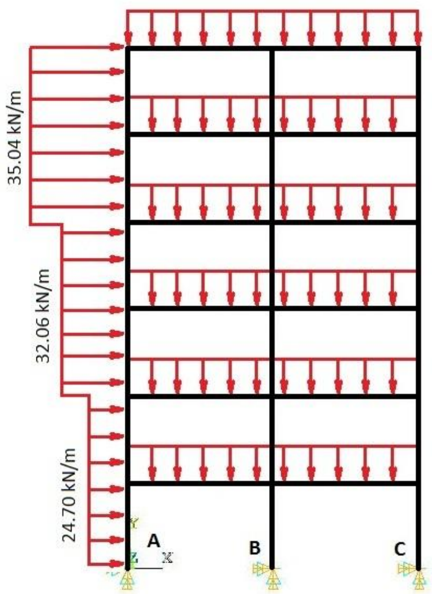
2.3 Optimized bracing by ERM

An unbraced frame with two bay and six-story is modeled as shown in Fig.5 (Mijar *et al.* 1998, Liang *et al.* 2000). A design domain is produced as shown in Fig.6 for developing a new bracing for application ERM. The design domain contains whole two bays, six-story. The steel building framework is fixed at points A, B and C, depending on the references (Mijar *et al.* 1998, Liang *et al.* 2000) two load cases are applied. The uniformly distributed load applied to floor beams is14.59 kN/m and wind loads are applied as horizontal distributed loads (Figs. 5(b) and 5(c)). The wide flange sections are used for 14 member groups and they are listed as W 8 X 21, W 8 X 28, W10 X 26, W 12 X 26, W 14 X 26, W 14 X 19, W 10 X 17, W 8 X 10, W 12 X 19, W 12 X 14, W 14 X 22, W 16 X26, W 16 X 31, and W 24 X 62. 2D solid element with plane stress is used with 0.0254 m thickness for the design domain. The Young's modulus (E) and density (ρ) are set to 200 GPa and 7800 kg/m^3respectively for all members.

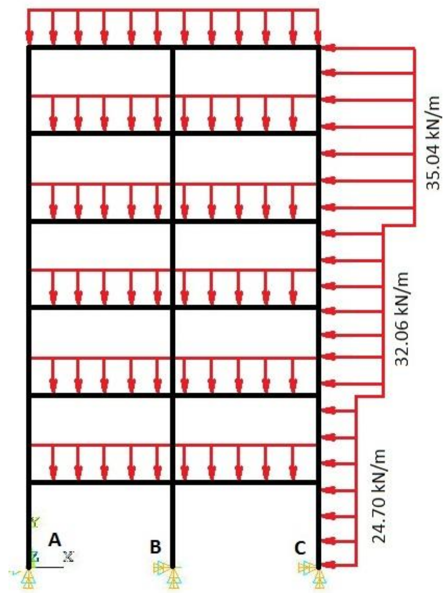
During modeling, ANSYS Beam elements are used for frames and Plane elements are used for planer design domain. Attachment of beam and plane elements are shown in Figs. 7 and 8.



(a) Geometry of unbraced frame



(b) Left side loading condition of frame



(c) Right side loading condition of frame

Fig. 5Unbraced frame with two bay and six-story (Mijar *et al.* 1998, Liang *et al.* 2000)

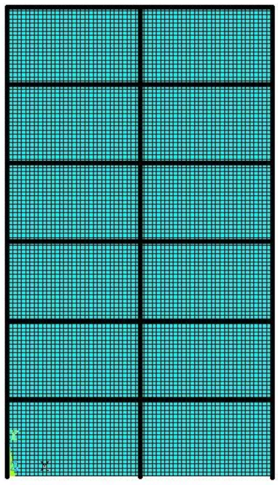
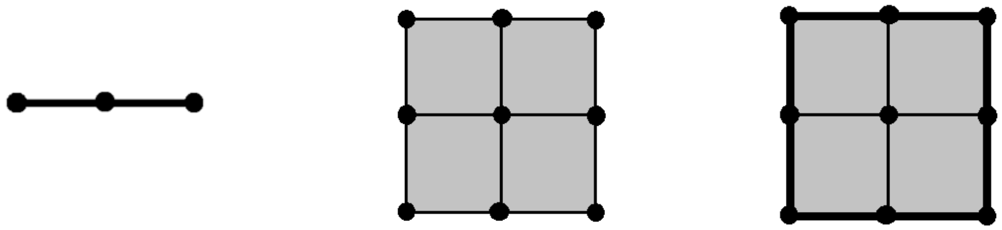
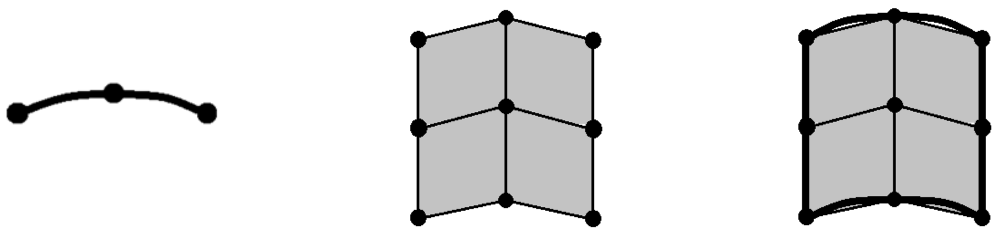


Fig. 6 Design domain with two bay and six-story



(a) Beam (b) Plane (c) Attached elements

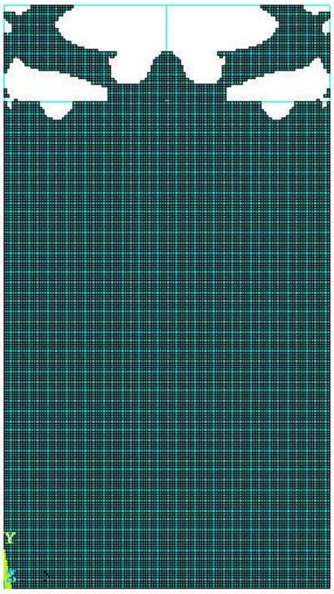
Fig. 7 Attaching of beam and plane elements. (a) Beam elements with UX, UY, ROTX, and ROTY, (b) plane elements with UX and UY, and ROTZ and (c) Attached beam and plane elements with nodes



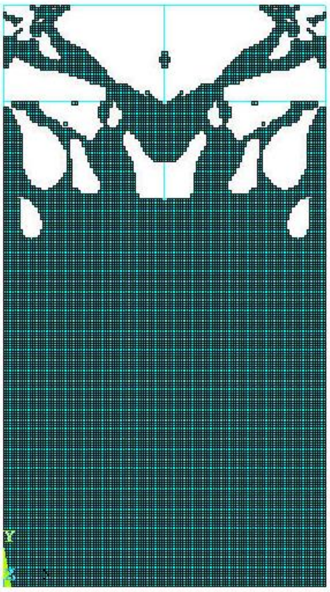
(a) Beam (b) Plane (c) Attached elements

Fig. 8 Deformed shapes of beam, plane, and attached elements

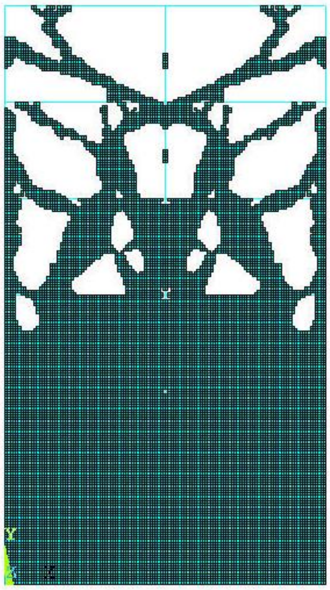
The design domain is optimized under the effect of wind loading conditions. This loading condition is reversed according to the fatigue type. The newly developed element removal algorithm is used for the optimization process. Volume reduction ratio of 75% is taken as the design constraint. In Fig. 9, some steps of the optimization process where by the final reduction ratio is reached are given. Optimized domain is obtained as shown in Fig. 10(a).



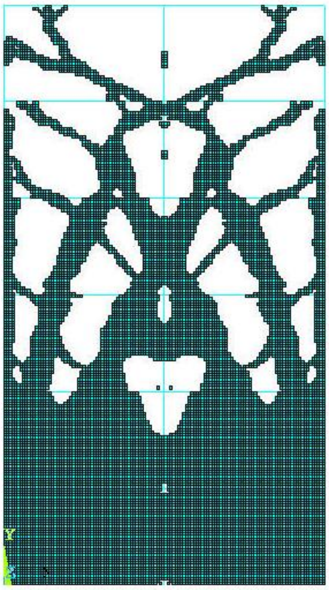
(a) Volume reduction of 10%



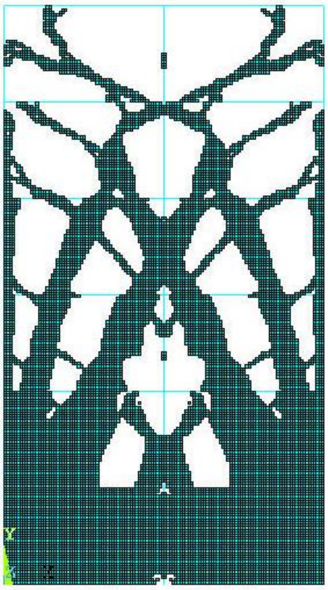
(b) Volume reduction of 20%



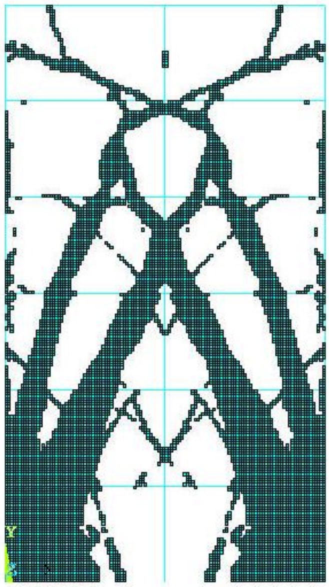
(c) Volume reduction of 30%



(d) Volume reduction of 40%

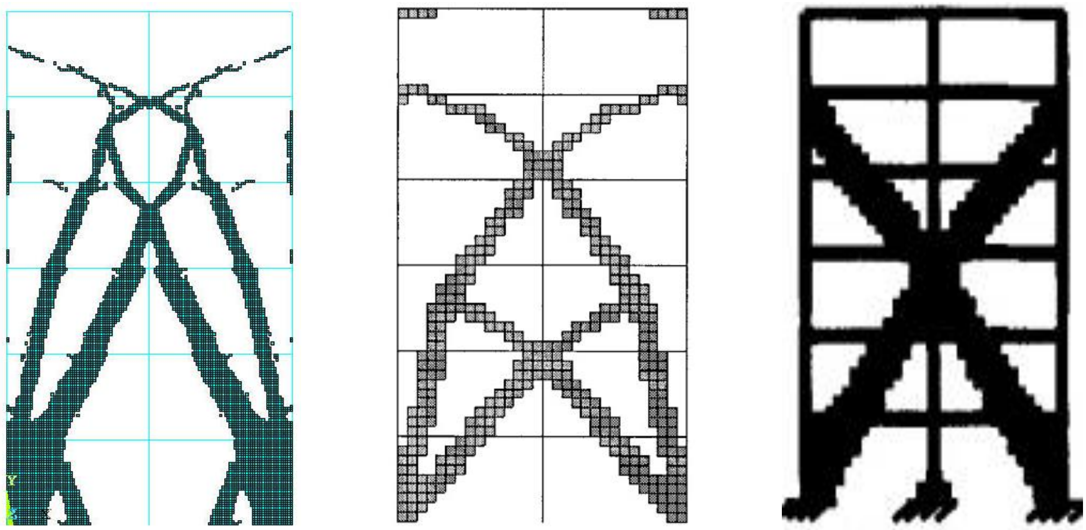


(e) Volume reduction of 50%



(f) Volume reduction of 60%

Fig. 9 Steps of Optimization



(a) 75% volume reduction

(b) 78% volume reduction (Liang *et al*. 2000)

(c) 74% volume reduction (Mijar *et al*. 1998)

Fig. 10 Optimized bracings

3. Results and discussion

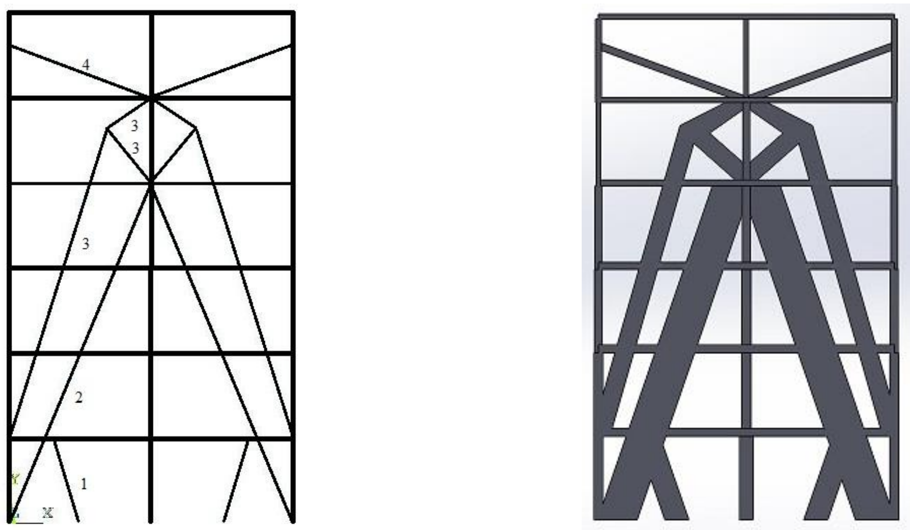
Results of ERM method is compared with the related literature in Fig. 10. For all the studies volume reduction ratio is about 75%. Slight differences can be observed in material distribution among the proposed solutions.

Hence optimization result presented in Fig. 10(a) is remodeled to obtain the final design as shown in Fig. 11. Cross-sectional dimensions (width x thickness) of the link 1: 1 x 0.0254 m, link 2: 1.65 x 0.0254 m, link 3: 0.8 x 0.0254 m, and link 4: 0.3 x 0.0254 m. Thicknesses of the links are same as that of the design domain which was considered to be constant thickness. Widths of the links are measured from Fig. 10(a) for Fig. 11.

For comparison, the results of different optimizations given in Fig. 10, braced and unbraced frames are modeled for the same loading and boundary conditions in line with the related literature. In the literature (Mijar *et al.* 1998, Liang *et al.* 2000) only deformation results are used as performance indicator. Definition of deformation is shown in Fig. 12 where the figure is obtained for unbraced frame at maximum deformation value. Deformation results (of Figs. 10(b), 10(c) and 11) are compared and the results are tabulated in Table 1.

In Table 1, deformation results of unbraced frame, optimized braced frame, and braced frames from the related literature are given. The comparison of the deformation between non-bracing result and literature results yields the 85.2% and 95.6% reduction in deformation while the optimized bracing yields 99.1% reduction in deformation. Maximum stress values for the references is not available hence comparison of stresses is not possible but maximum Von-Mises stress for optimized bracing is 69.6 MPa.

Proposed bracings are compared with each other in Table 2. When the proposed bracing systems are compared; the result obtained by Liang *et al*. (2000) is better than the result obtained by Mijar *et al*. (1998). The outcome of ERM yields 79% and 94% less deformation compared to the results obtained by Liang *et al*. (2000) and Mijar *et al*. (1998) respectively. In other words, the optimized bracing using ERM yields stiffer frames with the same amount of bracing material.



(a) Schematic view (b) Scaled drawing

Fig. 11 Remodeled optimized braced frame for wind loading

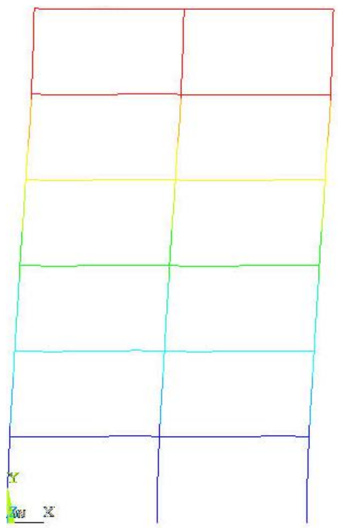


Fig. 12 Deformation result of unbraced frame

Table 1 Deformation results of bracing systems under the wind loading

No	Model	Max. Deform. mm	% Red.
1	Without bracing	547	-
2	Mijar *et al*. (1998)	81	85.2
3	Liang *et al*. (2000)	24	95.6
4	Optimized bracing	5	99.1

Table 2 Comparison of deformation results of bracing systems

	Model	Max. Deform. mm	% Red.
Compared models	Liang *et al*. (2000)	24	-
	Optimized bracing	5	79
Compared models	Mijar *et al*. (1998)	81	-
	Optimized bracing	5	94

4. Conclusions

To improve the strength of the structures, traditional bracing systems such as X, Y, V, or K types are used. In this study, topology optimization is applied on a simple steel structure to minimize the deformation of the structure under reversed wind load. Deformation result of the optimized frame and the related literature are compared.

An unbraced frame is modeled with two-bay and six-story (Mijar *et al.* 1998, Liang *et al.* 2000). Wind load is applied on both unbraced frame and optimized braced frame. When the deformation results are compared, bracing proposed by Mijar *et al*. (1998) provides 85.2% reduction while the one proposed by Liang *et al*. (2000) provides 95.6% reduction in deformation. The optimized braced frame which is obtained using ERM is the most rigid of them and provides 99.1% reduction in deformation relative to unbraced frame.

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