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Control the Effect of Wind Loads on Trussed Towers by Using Damping System

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Abstract: *It is very important to consider the effect of lateral loads induced from wind in the design of structures, especially for high-rise structures. The conventional way in limiting the wind drift in high structures was by changing the structural shape of the building to something more rigid and stable to reduce the deformation and increase stability. This paper is based on the study of adding damping to the trussed steel tower to reduce the effect due to wind over a tall structure by using a damping system. This analytical study is performed by modeling the trussed tower. The damping forces generated by the damper located at the ground level are transferred to the structure by the tendons that oppose the wind forces at each level of the structure. The effect of the damping system in controlling the response and the displacement of the structure under wind load was investigated. The dampers are ring spring friction devices consisting of inner and outer ring elements assemble to a form a spring interface. The results showed that the proposed damping system reduces response and displacement of the trussed tower under the influence of wind load significantly.*

Keywords: wind loads, velocity pressure, steel trussed tower, damping system, dampers.

1. INTRODUCTION

On September 11, 2015, a crawler crane toppled over onto the Masjid al-Haram, the Grand Mosque in Mecca, Saudi Arabia as shown in figure 1. More than one hundred people have been killed and nearly four hundred injured. The city was preparing for the Hajj pilgrimage. The crane collapsed through the roof of the third floor of the holy site as shown in figure 2. The strong wind of the storm was blamed for the deadly toppling of the crane that collapsed on one of Islam's holiest shrines in Mecca.

Wind loads, among other design loads, are crucial for the design of structures such as tall buildings, towers and communication antennas. Wind load is an environmental load associated with high degrees of variability and depends on wind speed, type of terrain surrounding the structure, wind fluctuation, height above ground, and exposed area. In order to design a structure to resist wind, the forces on the structure must be specified. Saudi Building Code SBC301 Loads and Forces Requirements, specify the methods of calculating wind loads on the structures which is adopted in this study. Most of trussed towers have insufficient lateral strength and resistance to input forces due to wind loads. The structural performance against wind load can be improved if the input energy in the structure can be absorbed by adding a type of supplemental damping system to the structure.

This research focused on adding damping in trussed tower structures using a damping system to implement control procedures. This technique can be used to mitigate the effects of wind loads on the response of trussed towers. The proposed damping system reduces the response of trussed towers to achieve the target displacement under wind loads.

Fig. 1. deadly crane collapsed in Mecca, Saudi Arabia.

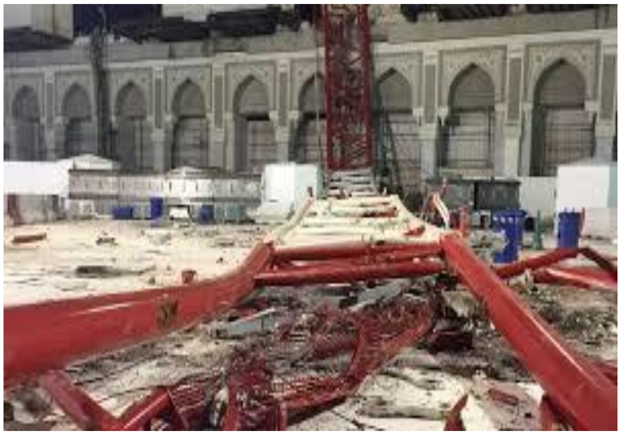


Fig. 2. the crane collapsed through the roof.

2. LATERAL WIND LOADS

The impact of lateral wind loads on a proposed communication trussed tower in Hail, Saudi Arabia was investigated. An analytical procedure in the structure whose design wind loads are determined in accordance with Saudi Building Code SBC 301-2007[1]. The wind load can be determined by calculating the basic wind speed in the region during the basic 3-second gust wind speed and in this case is equal to 180 km/h, in the selected area, Hail region, Saudi Arabia. Assuming that the structure is not subjected to the topographic effects, the topographic factor k_{zt} is 1.0 as per SBC Code. For towers with square cross section, the code defines the wind directionality factor k_d equals 0.85. The location on open terrain with scattered obstructions having heights generally less than 10m, surface roughness can be applied with exposure C and the building classification as an open building. For region where V is more than 160 km/h and the structure is classified under category 2, the importance factor (I) is equal to 1.0.

The velocity pressure q_z is determined by the following equation:

$$q_z = 0.0473 \times 10^{-3} k_z k_{zt} k_d V^2 I \quad (\text{kN}/m^2) \qquad (1)$$

Where:
k_z = the velocity pressure exposure
k_{zt} = the topographic factor.
k_d = wind directionality factor.
V = basic wind speed in km/h.
I = importance factor.

The Saudi Building Code SBC301 defines design wind loads in open buildings and other structures identified by the following formula:

$$F = q_z G C_f A_f \quad (\text{kN}) \qquad (2)$$

Where:
q_z = velocity pressure evaluated at height z.
G = gust effect factor.
C_f = net force coefficients.
A_f = projected area normal to the wind expected where C_f is specified for the actual surface area, m^2.

3. WIND LOADS ON THE PROPOSED TRUSSED TOWER

The proposed trussed tower is a square dimension in a plan of 5 x 5 m with a height of 50m. It consists of 10 levels of 5m for each level as shown in figure 3. The k_z velocity pressure coefficient varies with the elevation above the ground level z and calculates each height 5 m as shown in table1.

Table1: velocity pressure values on the total height of the structure.

Z (m)	k_z	q_z
50	1.40	1.81
45	1.37	1.77
40	1.34	1.73
35	1.30	1.68
30	1.26	1.63
25	1.21	1.56
20	1.16	1.5
15	1.08	1.4
10	1.00	1.29
5	0.86	1.12

Where:
k_z: depends on the position of the calculated point.
k_{zt} = 1.0, k_d = 0.85, V = 180km /h, I = 1.0

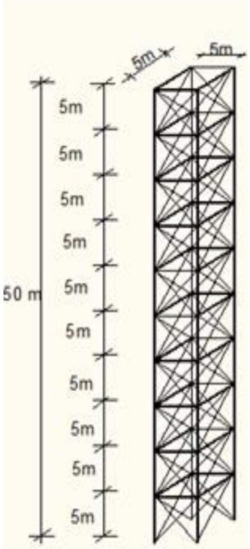


Fig. 3. the proposed steel trussed tower

For example, the velocity pressure at height 5.0m above the ground is equal to:
$q_z = 0.0473 \times 10^{-3} k_z k_{zt} k_d V^2 I = 1.12$ kN/m^2
The design wind loads on open building:
$F = q_z G C_f A_f$ (kN)
Where: G = gust effect factor = 0.85
G_f = force coefficient for trussed towers with square cross section:
$C_f = 4.0\varepsilon^2 - 5.9\varepsilon + 4.0$ (3)
Where: ε is ratio of solid area to gross area of one tower face for the segment under consideration.

For the proposed tower, the ratio can be taken equal to 10%, force coefficient C_f = 3.45. The tributary area at each level is equal to $25m^2$.The design wind load F can be calculated at each level of the total height 50m as shown in table 2.
For example: the design wind load at level 5m is equal to: $F_{5m} = 1.12 \times 0.85 \times 3.45 \times 25 = 82.1\ kN$

Table 2: the design wind load on the different level height of the structure.

Z (m)	$q_z (kN/m^2)$	$F\ (kN)$
50	1.81	132.7
45	1.77	129.7
40	1.73	126.8
35	1.68	123.2
30	1.63	119.5
25	1.56	114.4
20	1.5	110
15	1.4	102.6
10	1.29	94.6
5	1.12	82.1

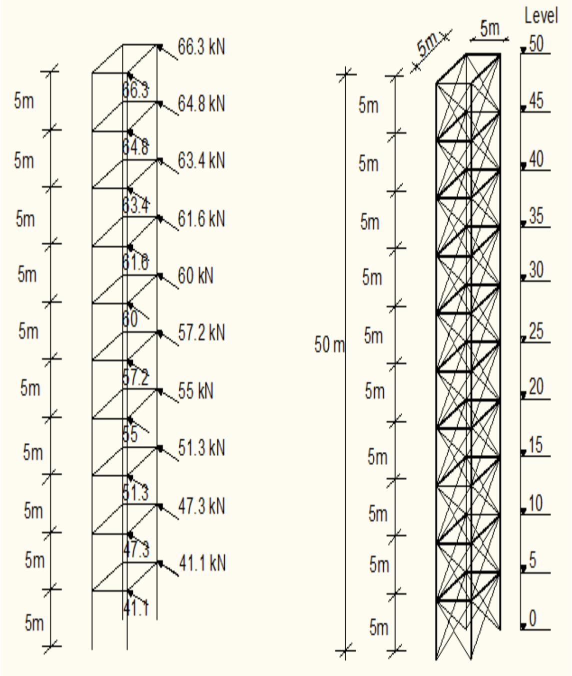
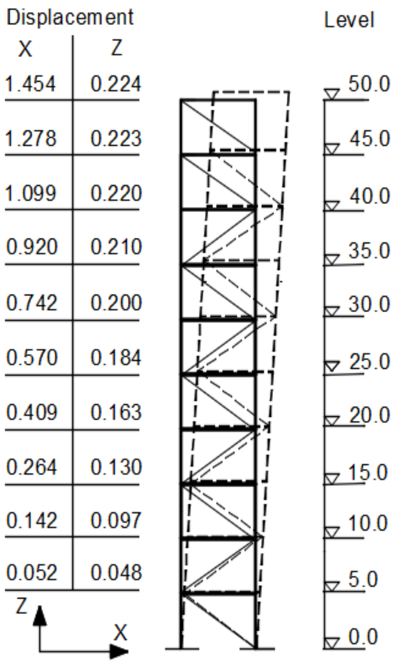


Fig. 4. design wind load on the proposed tower

The response of the structure due to wind load impact shown in table 3 can be determined using ETABS software [7] and shown figure 5.

Table 3: the horizontal displacement at each floor of the structure exposed to wind pressure.

Height Z (m)	Displacement (mm)
50	1454
45	1278
40	1099
35	920
30	742
25	570
20	409
15	264
10	142
5	52



Displacement X	Displacement Z	Level
1.454	0.224	50.0
1.278	0.223	45.0
1.099	0.220	40.0
0.920	0.210	35.0
0.742	0.200	30.0
0.570	0.184	25.0
0.409	0.163	20.0
0.264	0.130	15.0
0.142	0.097	10.0
0.052	0.048	5.0
		0.0

Fig. 5. deformed shape of the structure under the effect of wind pressure

To determine the target displacement, the top of the structure should not be distorted more than the target displacement. The target displacement can be determined from the following formula [2]:

$$X_{max} = \theta_{max} \; . H_{eff} \qquad (4)$$

Where: θ_{max} = Structural drift = 0.01
H_{eff} = Effective height = 0.7 H

The target displacement of the proposed structure = 0.01 (0.7 × 50) = 0.35m, which means the maximum displacement at the top of the structure should not exceed 350 mm. The ratio between the target displacements at the top of the structure under wind load to actual displacement is equals to 24%.

4. RING SPRINGS DAMPERS

Ring spring dampers have some features and characteristics that make them very useful as lateral control devices. Ring spring dampers are constructed of steel materials in which no possible leakage of liquid and no refilling or maintenance of any of the parts is needed which are potential problem in the viscous fluid dampers. Ring spring dampers absorb large amounts of the input energy with low weight and small size which is in contrast to typical viscous fluid dampers. However, viscous fluid dampers do not increase the stiffness of the structure and consequently the accelerations of the structure and its contents.

5. EFFECT OF RING SPRINGS IN ROCKING STRUCTURES

Rocking structures are uplift under sever lateral forces as shown in the figures 6. The first steel structure designed to rock was built in Wellington in 2007 idealized in figure 6-a. Here the self-centering cables are attached to springs at the bottom of the legs in figure 6-b. these springs increase the level of lateral inertia force under which uplift occurs, thereby increasing the secant stiffness and reducing the expected frame displacement.

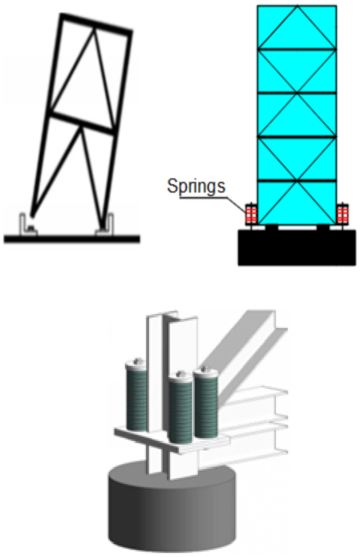


Fig. 6. schematic of rocking steel structure [6]

More recently other systems have been proposed and testing as shown in figure 7. Here, post- tensioned cables extend to the top of the structure. This results in larger member sizes throughout the frame than in the New Zealand approach, but it obviates the need for the springs.

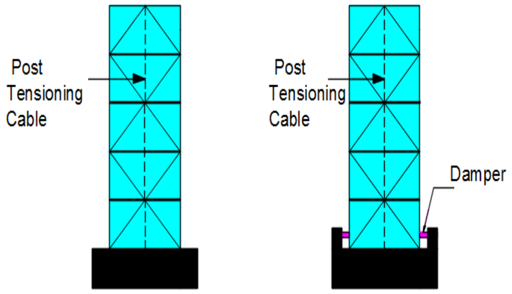


Fig. 7. different configuration for rocking structures [6]

Rocking structures can be used in low damage building construction. Their lateral strength is provided by a combination of gravity load effects, post-tensioning, gravity frame elastic effects and dissipaters. Without dissipaters they have statically self-centering characteristics. With dissipaters, they are likely to have small residual displacement displacements if the dissipater force is low. If the dissipater force is high, residual displacements may be removed by removing and then re-installing the dissipater attachment.

6. DAMPER-TENDON SYSTEM

The control method target reduced lateral demand via increased supplemental damping. This is achieved by dissipating input energy by means of specially designed non-structural elements or devices. The proposed damper-tendon system is composed of two major components, a tendon with high axial stiffness and a damper device located at the ground floor.

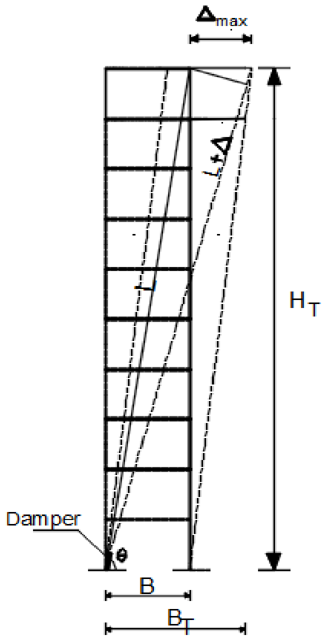


Fig. 8. The elongation in the supplemental damping system

From figure 8, the required damping forces produced in the ring spring dampers can be calculated as follows:

$$\tan\theta = \frac{H_T}{B} \quad , \quad \Delta = X_{max}.\cos\theta \quad (5)$$

Where:
Δ= total elongation in the system.
Area of the tendon cross section = 3260mm^2,
E = 200,000 MPa, Δ = 35 mm, L = 50.250 m

$$F = K.\Delta = \frac{EA}{L}\Delta = 454\ \text{kN}$$

7. THE RESPONSE OF THE STRUCTURE WITH THE SUPPLEMENTAL DAMPING SYSTEM

The structure was analyzed using ETABS software [7]. Wind loads are applied at each level of the structure. Damping forces of up to 454 KN were produced by the damper at the ground level and transferred along the straight tendon to the top of the structure as shown in figure 9.

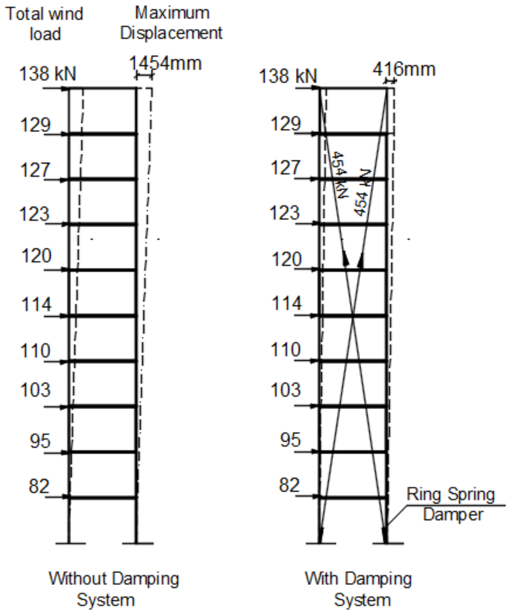


Fig. 9. displacement of the top of the structure with and without damping system.

The response of the structure with and without the supplemental damping system is shown in figure 9 and table 4. Significant reductions in the displacements of the structure were achieved. From table 4, adding damping to the structure using supplemental damping system reduce the top displacement from 1454 mm to 416 mm which is a 71% reduction in the displacement of the structure.

Table 4: reduction of the structural displacement

level	Displacement without the supplemental damping (mm)	Displacement with the supplemental damping (mm)	Reduction (mm)	%
10	1454	416	1038	71
9	1278	349	929	73
8	1099	282	817	74
7	920	213	707	77
6	742	142	600	81
5	570	88	482	85
4	409	53	356	87
3	264	26	238	90
2	142	10	132	93
1	52	0	52	100

8. SIZE OF THE DAMPER

The passive energy dissipater for dynamic wind load based on a self-centering friction mechanism is the ring spring. Ring springs are frictional devices consisting of inner and outer rings that have tapered mating surfaces as shown in figure 10.

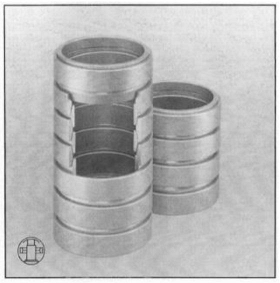


Fig. 10. prototype ring springs [8]

Spring column is loaded in compression or tension, the axial displacement is accompanied by sliding of the rings on the conical friction surfaces. The outer rings are subjected to circumferential tension (hoop stress), and the inner rings experience compression. Under the application of an axial load, the wedge action of the taper faces causes the inner elements to radially contract and the outer elements to radially expand, allowing axial deflection Sliding action between mating elements results in a large amount of energy being absorbed in overcoming the friction forces.

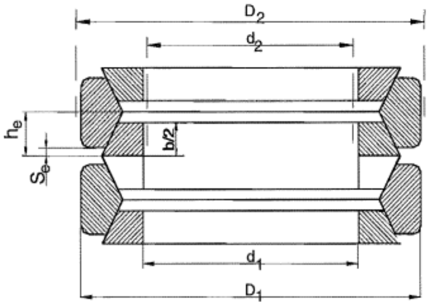


Fig. 11. dimensions of ring springs

F = spring end forces
S_e= spring travel for one element
W_e= energy absorption (work for one element)
h_e = element height
D_1, d_1= outer and inner diameter of the rings
D_2, d_2= outer and inner diameter
$b/2$= half width of ring
G_e= element weight

Table 5: Details of ring springs forces and dimensions [8]

F	S_e	W_e	h_e	D_1	d_1	b/2	D_2	d_2	G_e
(kN)	(mm)	(j)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(kg)
350	3.7	648	20	166	134	16	170	130	0.82
510	3.9	995	22.4	198	162	18.5	203	157	1.52
600	4.4	1320	23.4	194	155	19	199	150	1.06

The analytical results showed that the damping force equals to 454 kN is required to achieve the target displacement of the structure under the influence of wind loads. From table 5, the damper with an outer diameter D_2 = 203mm is capable of producing damping forces up to 510 KN, which means that the appropriate size of the ring spring damper with diameter of 20.3cm is sufficient to produce the required damping forces to control the impact of the wind loads on the structure.

9. CONCLUSION

This paper has focused on the effect of using supplemental damping system in reducing the response of the structure under the effect of wind load. The displacements and deformations of the structure can be greatly reduced without the need for increasing the stiffness and the member sizes of the primary structure. The dynamic response of the structure was controlled with adding damping by using the supplemental damping system to minimizing the effect of forces produced by the wind loads and to reduce the displacement of the structure. The incorporation of supplemental damping devices in the form of ring spring dampers provides the opportunity to move damage away from the primary structural elements. A simple 50 m height steel tower has been included to demonstrate the benefits of supplemental damper-tendon system in terms of controlling the displacement in the structures. The results showed that adding supplemental damping system to the structures can reduce significantly the response of the structure under applied lateral loads.

10. ACKNOWLEDGMENT

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