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INVERSE STRUCTURAL AIRFOIL: A NOVEL AND EFFECTIVE TOOLS FOR IMPROVEMENT OF THE BUILDINGS PERFORMANCE AGAINST WIND LOADS

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ABSTRACT

A novel instrument named inverse structural airfoil (ISA) is proposed in order to improve the performance of buildings against wind loads, which reduces wind-induced responses of mid to high-rise buildings. This tool can use for a new structures which are designing for wind load as well as one can use it for rehabilitation of existing buildings. An inverse airfoil is implemented, and so its lift-up force applies in the negative direction and works as lift-down force and this is useful for improvement of structures performance under wind loads and the detrimental effects of wind transfer to helpful effects. In this paper, the procedure that ISA works is explained, and then efficiency of ISA is investigated by using various types of ISA buildings in three wind zones with different wind velocity. Results show when ISA is employed in a structure system, the response of the structures against wind have been improved without any changes in the building configuration and the overall and inter-story drift, uplift forces at foundations, overturning moment of structures are reduced; on the other hand, with this tools, wind will be an effective and positive parameter in order to overcome detrimental effects of itself on the buildings.

Keywords: Inverse structural airfoil; wind loads; uplift; structural stability; lateral drift.

1. INTRODUCTION

The design of high-rise buildings has always faced to challenges. These challenges have caused to engineers for finding solutions for it to think. Some challenges in seismic design of high-rise buildings based on performance were well described and assessed [1]. [2] has been addressed the effects of wind load and related equivalent static wind loads on tall buildings.

A distribution of wind pressure at around four side of rectangular buildings has been

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experimentally evaluated by [3] and [4] presents dynamic analysis of tall building under wind load taking account of pulsation. A study on the available information with respect to wind loads on buildings has been done in [5].

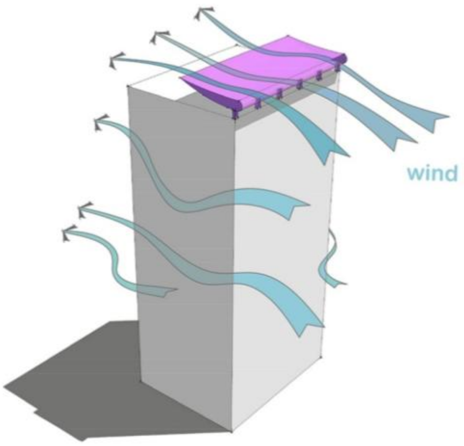
One of the challenges in the high-rise buildings due to wind load is uplift [6] force. In fact, extra forces because of wind velocity cause increasing the height of a building; hence, the possibility of occurrence of uplift and active moment around the heel rises in the structure, which may lead to rotation or overturning the structure.

To solve this problem, some solutions have been proposed; one of these ways is changing in the configuration of the building in plan or elevation in order to reduce the forces that are applied to structures due to wind, which this need some changes in architectural drawing and other considerations. Strengthening the structural foundation or utilizing piles under the foundation is another way in this regard. The foundations are placed on pile, the soil and piles stiffness control uplift [7]. An optimal grouting model is used for the complex foundation of an arch dam to reduce uplift [8]. Micro-piles with diameter of less than 30 cm and is length between 5 m to 10 m may efficiency control uplift [9].

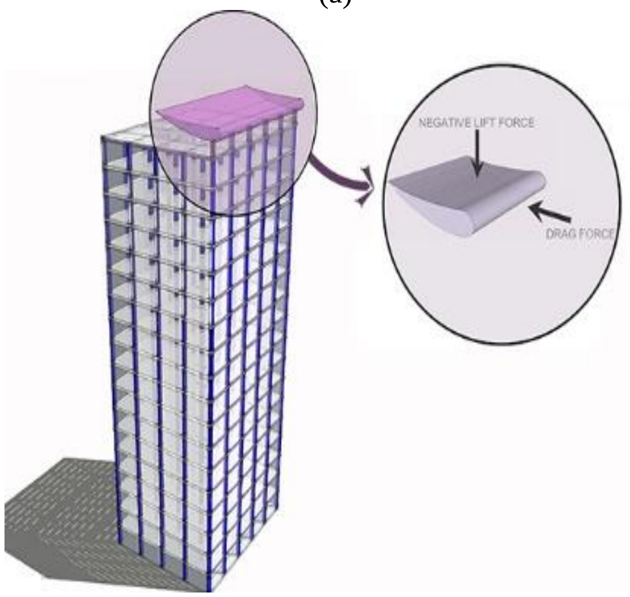
One of the solutions is using controlling systems that damping may reduce vibrations and displacements, so building can have more stability. An approach for designing a damper has been proposed to reduce the responses due to wind forces at a high-rise building [10]. A damping systems including: passive, active and semi-active dampers [11, 12]. Aerodynamics rules have an important role in the tall buildings performance against wind; hence, what is proposed in this paper using the idea of airfoil application in aircrafts, with difference placing on structure in reverse direction, which is called the Inverse Structural Airfoil (ISA). A good review on airfoils, its cross sections and configurations is summarized in [13]. In [14], Sapuppo and Archer have designed fully laminar flow airfoil shapes by the Stratford pressure gradient criterion.

For improving the stability and controlling of a race-car, designers proposed using inverse airfoils to produce negative lift [15] and in [16] an improvement of dynamic performance of the race-cars used inverse airfoil system to reduce dynamic force and improve stability is proposed. A study has been done on aerodynamic forces affecting a symmetric spoiler and a cambered spoiler to predict the negative lift force and drag force is done in [17] also, in [18] the researchers have tried to explain inverse airfoils with high negative lift force for race-cars and expression of challenges for designing some airfoil with high negative lift force for race-cars by [19]. The ground effect on the moment factor of inverse airfoils in a race-car was assessed to improved its performance [20] and in [21] effects of an airfoil with a gurney flap subject to ground effect have been assessed.

In this paper, as shown in Fig. 1-a, the inverse structural airfoil (ISA) at the roof of a building for reduction of the detrimental effects of wind forces applied on the structure, such as; uplift, drift ratio, overturning moment and to following it, increasing safety factor of structure against overturning moment. With mounting airfoil at the top of the structure, a drag force in the direction of wind blow and a negative lift force in the transversal direction (respect to wind blow) are applied on the structure (see Fig. 1-b). As all of building codes say a structure under wind load must be designed in both direction so, ISA should be mounted in both two directions of structure axes and both two its orientation to wind flow any direction or orientation (in Fig. 1, only one of these two is shown, because of simplicity). An ISA could play its rules well at responses reduction and increasing safety factor for both directions, but in this paper, ISA has been mounted in one direction and one orientation, because of that main goal of this research had just been investigating the effects of ISA in building and more over the buildings that are studied here, are symmetric respect to their axes.



(a)



(b)

Figure 1. (a) Use of Inverse Structural Airfoil (ISA) as a useful tools in structure for reduction the detrimental effects of wind forces, (b) lift-down and drag forces on ISA due to wind

The results of this research show that implementing ISA reduces structural responses and increases safety factor against wind loads; therefore, the proposed ISA can be used as an effective instrument for improving the performance of structures under wind loads.

2. AIRFOIL MECHANISM AND WIND FORCES

Airfoil mechanisms are such that prepare aircraft wings for a proper lift to pilot can take off the ground in a better position. Also, this case can be used for race-cars so that produce a negative lift using a reverse airfoil to properly improve the stability of the structure, consequently, it can be used for tall buildings so that an inverse structural airfoil installed on top of the structure and its negative lift lead to satisfactory results, which is interested in civil engineering.

One of the most important features of the airfoil is the geometry, which have high importance. The geometry of an airfoil will be defined by coordinates of upper surface and lower surface which is including the parameters of maximum thickness, maximum camber, position of maximum thickness, position of maximum camber and the nose radius as shown in Fig. 2, which these parameters in turn can effect on the performance of the airfoil so that it can be produced an airfoil section with having these parameters.

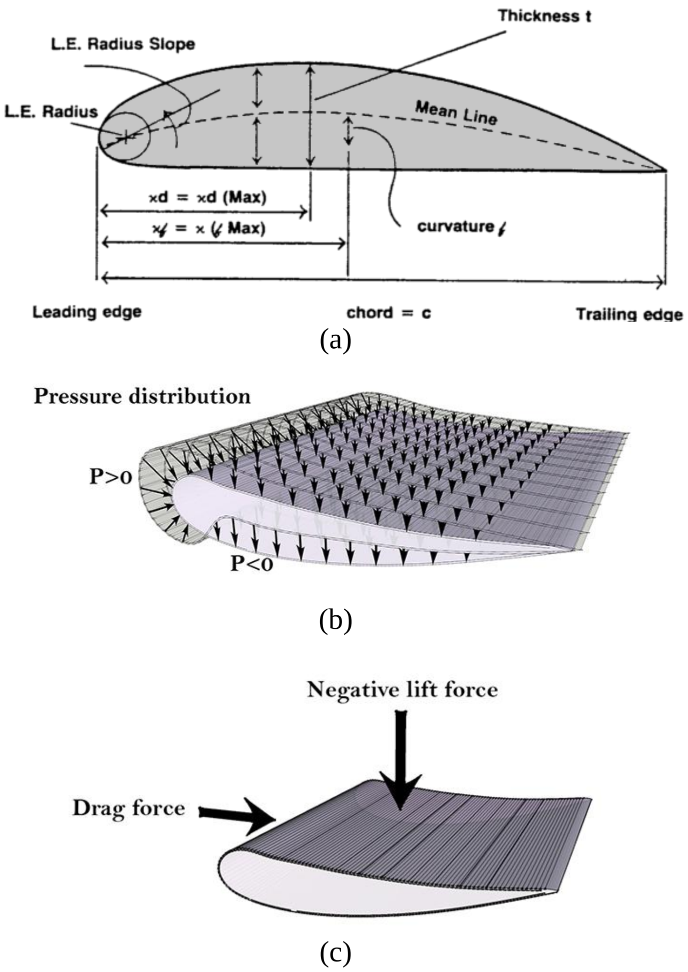


Figure 2. Airfoil structure; (a) geometry of airfoil, (b) pressure distribution on Inverse Structural Airfoil (ISA) due to wind and (c) resultant negative lift and drag forces on ISA

Aerodynamic performance of airfoil sections is mainly evaluated by the pressure distribution at its upper surface that pressure distribution is expressed by the pressure coefficient (C_p) which is the difference between the local static pressure and the static pressure free stream. Designing an airfoil is required to have a proper understanding of the characteristics of the boundary layer and the relationship between geometry and pressure distribution; depending on the purpose of the airfoil design, the design method may be different, for example, some sections have a low drag and a given lift or drag is not important and the maximum lift is required [10], also for more details related properties of airfoils see [22-27]. In this research, an airfoil section with high lift and low drag effects was required, thus it has been tried to use a series of available airfoil sections with complete specifications then a proper airfoil is selected from among them, and finally, we used the airfoil of NACA0012 with a suitable attack angle which has high lift and aspect ratio [16]. Following equations is used in order to calculate the lift and drag forces on the airfoil due to wind [18],

$$F_L = \frac{1}{2}\rho C_L {V_z}^2 S \tag{1}$$

$$F_D = \frac{1}{2}\rho C_D {V_z}^2 S \tag{2}$$

where, ρ is the mass density of air, C_L and C_D are the lift and drag coefficients respectively, S is the wing area, V_z is the wind velocity along at the structure roof level (Z) (e.g., the ISA is installed at the roof level of the structure) and is determined by [28],

$$V_z = V_g\left(\frac{Z}{Z_g}\right)^{1/\alpha} \tag{3}$$

in which, V_g is the gradient wind velocity assumed constant above the boundary layer, Z_g is nominal height of boundary layer, which depends on the exposure and α is power law coefficient and in this study, urban and suburban terrain considered where in [22] is named as exposure B.

For evaluating the wind velocity and wind loads which effect on the structures, the National Building Code of Canada (NBCC-2005) [29] is used and according to NBCC, the specified external pressure duo to wind on part or all of a surface of a building shall be calculated as,

$$p = I_W q C_e C_g C_p \tag{4}$$

where, p is the specified external pressure acting statically and in a direction normal to the surface, either as a pressure directed towards the surface or as a suction directed away from the surface, I_w is importance factor for wind load, C_e is exposure factor, C_g is gust effect factor, C_p is external pressure coefficient, averaged over the area of the surface considered, q is reference velocity pressure in kN/m^2,

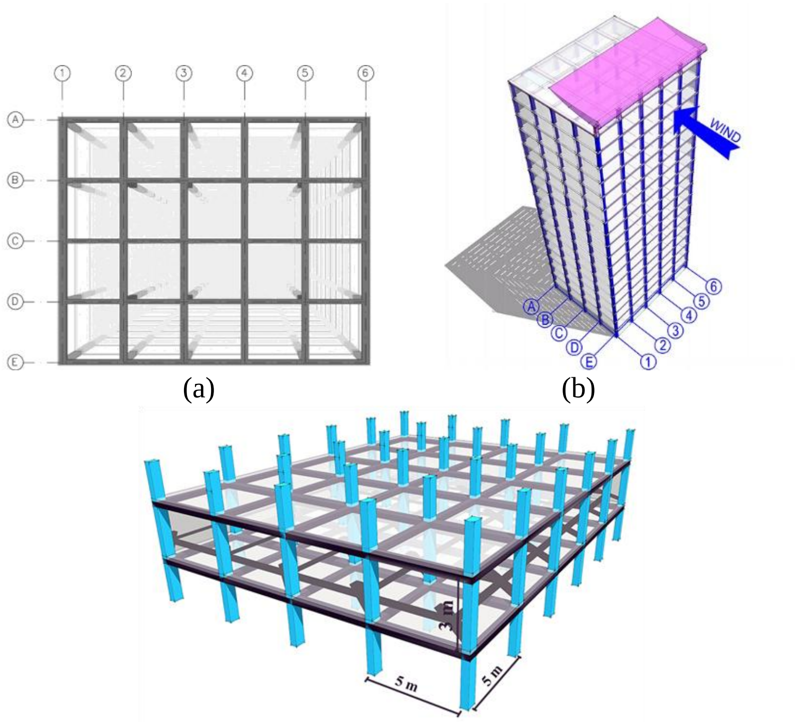
$$q = 0.0000613V^2 \tag{5}$$

and in this equation, V is wind velocity on a given region in *km/h*.

3. THE MODEL

In order to evaluate the performance of ISA on structure as a useful instrument to prevent the structures against detrimental effects of wind forces and improvement of structure responses, two 17 stories and 30 stories buildings with the overall height 51*m* and 90m, respectively, is considered (see, Fig. 3-b). In this study, ISA is mounted at the roof level of the structures and for simplicity and because of the symmetric of the structures, the analysis is done for on direction, as shown in Fig. 3-b.

These buildings are steel moment resistance frame structures with structural steel ST37 and f_y=2400 kg/cm^2, which have dimensions of 25×20 m^2 (Fig. 3-a) and all spans are 5m and height of any story is 3 *m* (Fig. 3-c) and the structures are designed according the building codes in order to prepare a good capacity against gravity and lateral loads and the suitable cross section for the columns is selected as box and for the beams as I-shaped sections, the summary details of the structural elements of these building is illustrated in Table 1, (it should be noted that in order to reduce the complexity and better comparison of the results, all structures under all conditions are designed and the critical case which is involved with the larger element cross section is implemented).

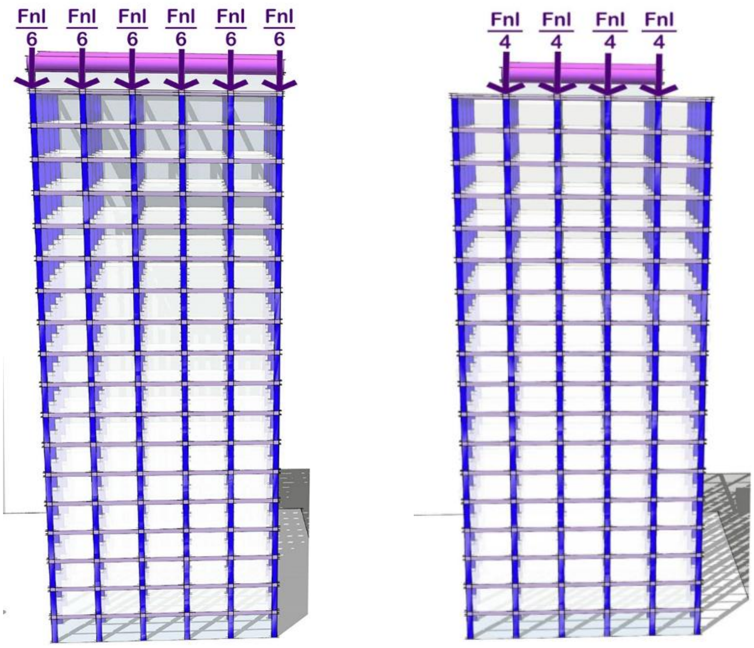


(c)

Figure 3. The structural model; (a) typical plan and grid axes data, (b) 3D view of the model and the location of the ISA and (c) dimensions of the model

Table 1. The properties of the structural elements in both buildings (structural material is ST37 steel with f_y=2400 *kg/cm*^{2}).

Building	**Stories range**	**Beam (I-shaped section)**				**Column (Box section)**	
		Flange		Web		Width (cm)	Thickness (cm)
		Width (cm)	Thickness (cm)	Width (cm)	Thickness (cm)		
7 stories	1~6	40	1.5	80	2.0	60	2.0
	7~12	30	1.0	60	1.5	50	2.0
	13~17	30	1.0	50	1.0	40	1.5
30 stories	1~10	40	1.5	80	2.0	80	3.0
	11~20	30	1.0	60	1.5	70	3.0
	21~30	30	1.0	50	1.0	60	2.5



(a) (b)

Figure 4. Distributions of negative lift forces at columns; (a) for ISA with dimensions of 25×5 and (b) for ISA with dimensions of 23×4 (Fnl, is total negative lift force on ISA due to wind)

For better understanding of efficiency of ISA on the performance of the structures, three levels of wind velocities of 85 *km/h*, 105 *km/h and* 130 *km/h* with gradient velocities of 197 *km/h*, 244 *km/h* and 299 *km/h*, respectively, is used and under these three wind conditions, 4 configuration types of ISA is utilized as is described in Table 2; without ISA, with ISA at two size (23×4 m^2 and 25×5 m^2) and ISA (23×4 m^2) with double slotted flap. These ISA are mounted at the structures as shown in Fig. 4; the ISA with dimensions of 23×4 is put on four intermediate columns of frame at axis E and the ISA with dimensions of 25×5 is put on all columns of E frame; as the roof diaphragm is rigid, therefore lift and drag forces produced at small and large airfoils applied on four intermediate columns (Fnl/4) and all columns of E frame (Fnl/6), respectively.

Table 2: Types and characteristics of ISA that is utilized for the buildings.

Type of Inverse Structural Airfoil	Model name
Without ISA (None)	A0
ISA with dimensions of 23×4	A1
ISA with dimensions of 25×5	A2
ISA of double slotted flap with dimensions of 23×4	A3

The performance of an airfoil system is strongly depends on the wind attack angle [16], so herein, wind attack angle and Reynolds number of the ISA (which is used in this study based on airfoil section of NACA0012) is equal to 15° and 10^{7}. For the ISA with two split-flaps, the lift coefficient C_L due to the flap will increase by [18]:

$$\Delta C_L = 1.6\frac{\tilde{c}}{c} \tag{6}$$

where, $\tilde{c}$ is flap length and c is chord length of airfoil.

Table 3: The components of the drag and lift forces on the different types of the ISA for any buildings and wind region

Building	**Force component (ton)**	**Wind velocity (km/h)**								
		85			**105**			**130**		
		A1	**A2**	**A3**	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
17 stories	Lift force	131.15	178.19	178.21	200.13	271.91	271.94	306.77	416.81	416.85
	Drag force	1.45	1.97	1.45	2.21	3.00	2.21	3.39	4.60	3.39
	Lift of per column	32.79	29.7	44.55	50.03	45.32	67.98	76.69	69.47	104.21
	Drag of per column	0.36	0.33	0.36	0.55	0.50	0.55	0.85	0.77	0.85
30 stories	Lift force	154.26	209.59	209.61	235.39	319.82	319.85	360.83	490.25	490.29
	Drag force	1.70	2.32	1.70	2.60	3.53	2.60	3.99	5.42	3.99
	Lift of per column	38.56	34.93	52.4	58.85	53.3	79.96	90.21	81.71	122.57
	Drag of per column	0.43	0.39	0.43	0.65	0.59	0.65	1.00	0.90	1.00

4. RESULTS AND DISCUSSION

All models have been analyzed using finite element code and the components of the response of the structures are captured and performance of the various types of ISA on both buildings and in different wind region is evaluated by comparison of the results components such as uplift forces at supports (Fig. 5), safety factor of against overturning moment (Fig. 6) and drifts (Fig. 7). In these figures, the improvement percentage (PRI) of the related component is calculated by,

$$\text{PRI} = \frac{V_{WA} - V_{WOA}}{VWOA} \times 100 \qquad (7)$$

where, V_{WA} is the value of related component with ISA and V_{WOA} is the value of related component without ISA.

4.1 Effect of ISA on uplift force

Tables 4 and 5 show the absolute values of uplift force for any cases (as described above) for 17 stories and 30 stories building, respectively, as well as Fig. 5 shows how using the ISA reduces uplift in a structure; in this figure, each label at horizontal axis mentions the specify column is considering to measurement of the uplift and in these figures, because of symmetry, for each axis D and E, only the results for columns which are located at axes 1,2 and 3 is captured and results at axes 5 4, 5 and 6 is omitted; moreover, the amount of larger than 100 for PRI at any point expresses that using ISA in the structure cause remove uplift at that point and on the other hand, at such a this points, ISA changed lift-up forces at column support into lift-down forces (for example, see columns at D1, D2 and D3).

Table 4: Absolute values of uplift force for each column location, all ISA types, three wind velocity and related PRI for 17 stories building

	Column label	**A0**	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**
wind velocity = 85 km/h	E1	-33.58	-24.42	27.3	17.04	150.7	23.6	170.28
	D1	-5.73	-1.3	77.3	33.07	677.1	44.88	883.25
	E2	-34.86	-18.5	46.9	15.49	144.4	32.12	192.14
	D2	-6.05	1.21	120.0	32.97	645.0	48.41	900.17
	E3	-35.17	-15.16	56.9	15.11	143.0	36.76	204.52
	D3	-6.19	2.8	145.2	32.89	631.3	50.62	917.77
	E4	-35.17	-15.16	56.9	15.11	143.0	36.76	204.52
	D4	-6.19	2.8	145.2	32.89	631.3	50.62	917.77
	E5	-34.86	-18.5	46.9	15.49	144.4	32.12	192.14
	D5	-6.05	1.21	120.0	32.97	645.0	48.41	900.17
	E6	-33.58	-24.42	27.3	17.04	150.7	23.6	170.28
	D6	-5.73	-1.3	77.3	33.07	677.1	44.88	883.25
wind velocity = 105 km/h	E1	-51.24	-37.27	27.3	-19.32	62.3	-31.97	37.61
	D1	-8.75	-1.99	77.3	5.15	158.9	0.5	105.71
	E2	-53.2	-28.22	47.0	-21.68	59.2	-18.97	64.34
	D2	-9.23	1.84	119.9	4.99	154.1	5.89	163.81
	E3	-53.67	-23.14	56.9	-22.26	58.5	-11.89	77.85
	D3	-9.44	4.27	145.2	4.87	151.6	9.26	198.09

wind velocity = 130 km/h	E4	-53.67	-23.14	56.9	-22.26	58.5	-11.89	77.85
	D4	-9.44	4.27	145.2	4.87	151.6	9.26	198.09
	E5	-53.2	-28.22	47.0	-21.68	59.2	-18.97	64.34
	D5	-9.23	1.84	119.9	4.99	154.1	5.89	163.81
	E6	-51.24	-37.27	27.3	-19.32	62.3	-31.97	37.61
	D6	-8.75	-1.99	77.3	5.15	158.9	0.5	105.71
	E1	-78.52	-57.12	27.3	-29.6	62.3	-49	37.60
	D1	-13.41	-3.05	77.3	7.9	158.9	0.77	105.74
	E2	-81.53	-43.26	46.9	-33.22	59.3	-29.07	64.34
	D2	-14.14	2.83	120.0	7.65	154.1	9.02	163.79
	E3	-82.25	-35.46	56.9	-34.1	58.5	-18.21	77.86
	D3	-14.47	6.55	145.3	7.47	151.6	14.2	198.13
	E4	-82.25	-35.46	56.9	-34.1	58.5	-18.21	77.86
	D4	-14.47	6.55	145.3	7.47	151.6	14.2	198.13
	E5	-81.53	-43.26	46.9	-33.22	59.3	-29.07	64.34
	D5	-14.14	2.83	120.0	7.65	154.1	9.02	163.79
	E6	-78.52	-57.12	27.3	-29.6	62.3	-49	37.60
	D6	-13.41	-3.05	77.3	7.9	158.9	0.77	105.74

Table 5: Absolute values of uplift force for each column location, all ISA types, three wind velocity and related PRI for 30 stories building

	Column label	A0	A1	PRI	A2	PRI	A3	PRI
velocity of wind = 85 km/h	E1	-115.49	-102.82	11.0	-58.93	49.0	-45.47	60.63
	D1	-31.33	-23.75	24.2	15.99	151.0	31.51	200.57
	E2	-119.13	-103.02	13.5	-62.77	47.3	-44.42	62.71
	D2	-32.48	-23.1	28.9	14.95	146.0	32.8	200.99
	E3	-120.15	-101.75	15.3	-63.87	46.8	-42.32	64.78
	D3	-32.99	-22.28	32.5	14.48	143.9	34.1	203.36
	E4	-120.15	-101.75	15.3	-63.87	46.8	-42.32	64.78
	D4	-32.99	-22.28	32.5	14.48	143.9	34.1	203.36
	E5	-119.13	-103.02	13.5	-62.77	47.3	-44.42	62.71
	D5	-32.48	-23.1	28.9	14.95	146.0	32.8	200.99
	E6	-115.49	-102.82	11.0	-58.93	49.0	-45.47	60.63
	D6	-31.33	-23.75	24.2	15.99	151.0	31.51	200.57
wind velocity = 105 km/h	E1	-177.44	-158.1	10.9	-141.16	20.44635	-150.55	15.15
	D1	-48.14	-36.56	24.1	-27.4	43.1	-32.21	33.09
	E2	-183.03	-158.44	13.4	-147.09	19.6	-148.99	18.60
	D2	-49.9	-35.59	28.7	-28.98	41.9	-30.24	39.40
	E3	-184.6	-156.51	15.2	-148.78	19.4	-145.79	21.02

	D3	-50.68	-34.35	32.2	-29.7	41.4	-28.27	44.22
	E4	-184.6	-156.51	15.2	-148.78	19.4	-145.79	21.02
	D4	-50.68	-34.35	32.2	-29.7	41.4	-28.27	44.22
	E5	-183.03	-158.44	13.4	-147.09	19.6	-148.99	18.60
	D5	-49.9	-35.59	28.7	-28.98	41.9	-30.24	39.40
	E6	-177.44	-158.1	10.9	-141.16	20.4	-150.55	15.15
	D6	-48.14	-36.56	24.1	-27.4	43.1	-32.21	33.09
wind velocity = 130 km/h	E1	-271.94	-242.29	10.9	-221.37	18.6	-230.76	15.14
	D1	-73.77	-56.03	24.0	-44.8	39.3	-49.37	33.08
	E2	-280.5	-242.81	13.4	-230.41	17.9	-228.36	18.59
	D2	-76.47	-54.54	28.7	-47.25	38.2	-46.36	39.37
	E3	-282.91	-239.85	15.2	-232.99	17.6	-223.46	21.01
	D3	-77.67	-52.63	32.2	-48.36	37.7	-43.33	44.21
	E4	-282.91	-239.85	15.2	-232.99	17.6	-223.46	21.01
	D4	-77.67	-52.63	32.2	-48.36	37.7	-43.33	44.21
	E5	-280.5	-242.81	13.4	-230.41	17.9	-228.36	18.59
	D5	-76.47	-54.54	28.7	-47.25	38.2	-46.36	39.37
	E6	-271.94	-242.29	10.9	-221.37	18.6	-230.76	15.14
	D6	-73.77	-56.03	24.0	-44.8	39.3	-49.37	33.08

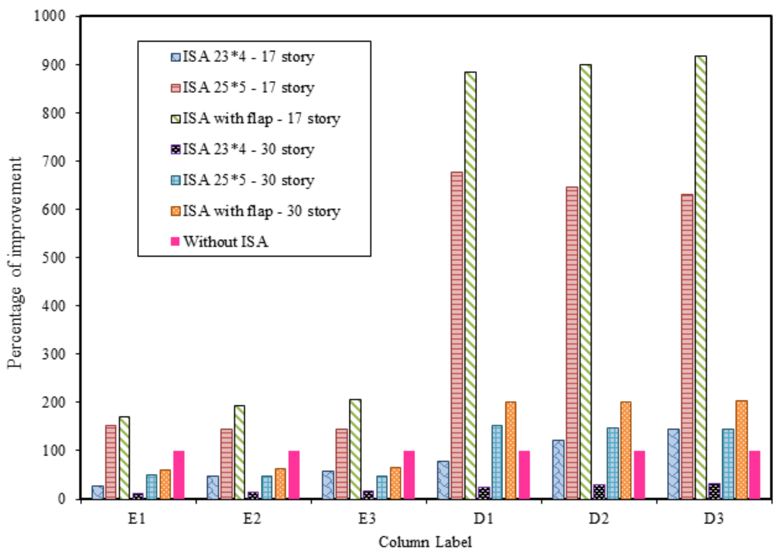
Fig. 5-a depicts the results for both buildings which are subjected to wind with velocity of 85 km/h; as it is clear, in 17 story building, uplift values at E1 column at any 4 cases of A0 , A1 , A2 , A3 is respectively equal to -33.58, -24.42, 17.04 , 23.6 and PRI is equal to 27.3, 150.7 and 170.3 (see Table 4). It is obviously clear that adding ISA to the structural system reduces the uplift force and between there three types of ISA which is studied here, A3 has the better performance rather than other two types. This trend is similarity repeated for other columns whether at 17 stories building or at 30 stories building.

The results for 17 story building similarity also show that uplift value at D1 column at 4 cases consist of A0, A1, A2, A3 is equal to -5.73, -1.3, 33.03, 44.88, respectively and PRI is equal to 77.3, 677.1 and 883.2 (Table 4); what it must be implied here is that the value of uplift reduction at D1 column is less than E1 column but its PRI is larger; because of that uplift values at D frame is less than E frame, therefore frame E is more important than D frame and in general, it is achieved satisfactory results. This matter is observed at other columns of two frame and both buildings.

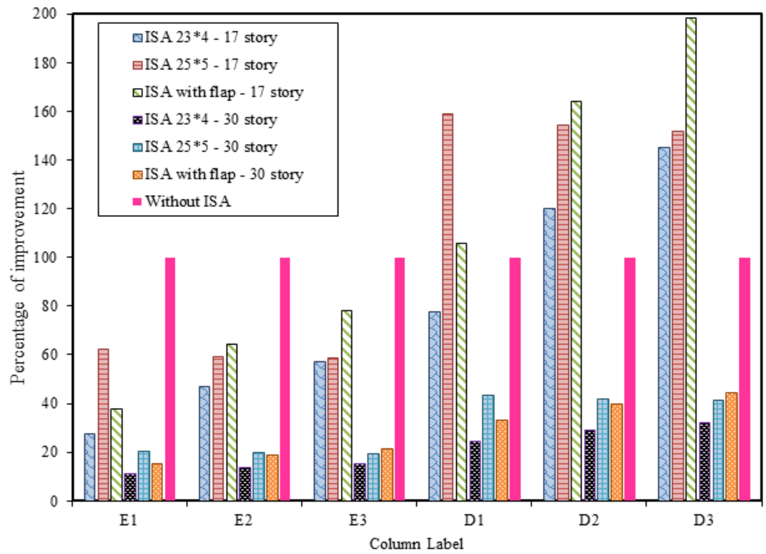
Results for effect of ISA on uplift force for the wind with velocity 105 km/h is shown in Fig. 5-b, for the case of 17 story building, uplift value at E1 column at 4 cases consist of A_0 , A_1 , A_2 , A_3 is equal to –51.24, -32.27, -19.32, -31.97 and PRI is 27.3, 62.3 and 37.6, respectively (see Table 4); as is clear, PRI for the ISA type A1 is less than A2 and the most improvement in uplift force is happened when ISA type A3 is used; thus at E1 column which is a side column, A2 leads to a better results; it should be noticed that for wind velocity 85 km/h, ISA type A3 led to better results. The value of PRI related to uplift force at D1 is similar to E1, and this is because of D is a interior frame and E is side frame.

Comparison between results for 17 and 30 stories buildings shows that PRI of uplift at intermediate columns is same as figure whether saw and in addition ISA type A3 leads to best results.

Fig. 5-c also has a trend like to Fig. 4-b; and comparison the results that is captured in this figure say, increasing in wind velocity cause reduction in performance of the ISA in order to improvement of uplift force, and in all cases, ISA works as an effective tools for improvement and reduction of the values of uplift forces and change those into useful lift-down forces.



(a)



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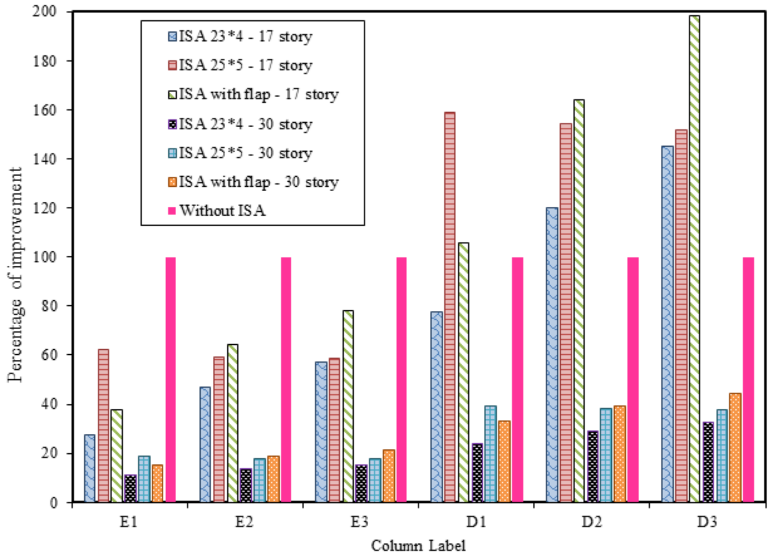


(c)

Figure 5. Percentage of change in uplift forces due to wind; (a) for wind with *V*=85 *km/h*, (b) V=105 km/h and (c) V=130

As it is obviously observed in Figs. 5, the uplift force at each column support has been considerably reduced; also it is shown that the reduction in percentage of uplift at ISA type A2 is more than ISA type A1 and the most reduction in percentage of uplift is related to ISA type A3; therefore it could be received that using an ISA with flap is more logical and appropriate, on the other hand, ISA type A3 (e.g., its dimensions is 24×4) have smaller dimensions rather than ISA type A2 (e.g., its dimensions is 25×5) and also leads to partially better results for reduction the percentage of uplift forces, it means, uplift force PRI for 17 stories building is larger than 30 stories building and the uplift PRI is decreased with increasing wind velocity from 85 km/h to 130 km/h; so, therefore slower wind velocity have better effect on the performance of ISA for controlling the uplift forces,

4.2 Effect of ISA on overturning moment

The values of the active and resistance overall moment of the structures to all wind cases for both buildings in the presence of any types of ISA and also the original buildings without ISA is reported in Table 6; As is mentioned in this table, ISA increase values of both active and resistance moment and its reason is that, using ISA causes additional lift-down and drag forces and the drag force will subject the structure under additional active moment and the lift-down force increases the overall resistance moment, this is happened lift-down force is much larger than drag force and because of that as shown in Table 6 and Fig. 6, in all cases, ISA improved the performance of the structure regarding overturning moment.

Table 6: Values of overall active and resistance moment and stability safety factor and related PRI due to any kind of ISA

	Wind velocity (km/h)	Parameter	A0	A1	PRI	A2	PRI	A3	PRI
17 stories building	85	Active moment	4820.79	4895.58	1.55	4923.01	2.12	4895.58	1.55
		Passive moment	11717.70	14340.70	22.38	15281.50	30.41	15281.90	30.42
		Safety factor	2.43	2.93	20.52	3.10	27.71	3.12	28.42
	105	Active moment	7356.33	7470.60	1.55	7512.15	2.12	7470.60	1.55
		Passive moment	11717.70	15720.36	34.16	17155.90	46.41	17156.50	46.42
		Safety factor	1.59	2.10	32.11	2.28	43.37	2.30	44.18
	130	Active moment	11273.90	11449.87	1.56	11512.93	2.12	11450.50	1.57
		Passive moment	11717.70	17853.10	52.36	20053.90	71.14	20054.50	71.15
		Safety factor	1.04	1.56	50.02	1.74	67.59	1.75	68.51
30 stories building	85	Active moment	16933.21	17091.73	0.94	17145.31	1.25	17089.49	0.92
		Passive moment	21114.30	24199.50	14.61	25306.10	19.85	25306.50	19.85
		Safety factor	1.25	1.42	13.55	1.48	18.37	1.48	18.76
	105	Active moment	26015.57	26257.44	0.93	26344.88	1.27	26253.71	0.92
		Passive moment	21114.30	25822.10	22.30	27510.70	30.29	27511.30	30.30
		Safety factor	0.81	0.98	21.17	1.04	28.67	1.05	29.12
	130	Active moment	39870.01	40182.96	0.78	40372.35	1.26	40240.63	0.93
		Passive moment	21114.30	28330.70	34.18	30919.30	46.44	30920.10	46.44
		Safety factor	0.53	0.71	33.13	0.77	44.62	0.77	45.09

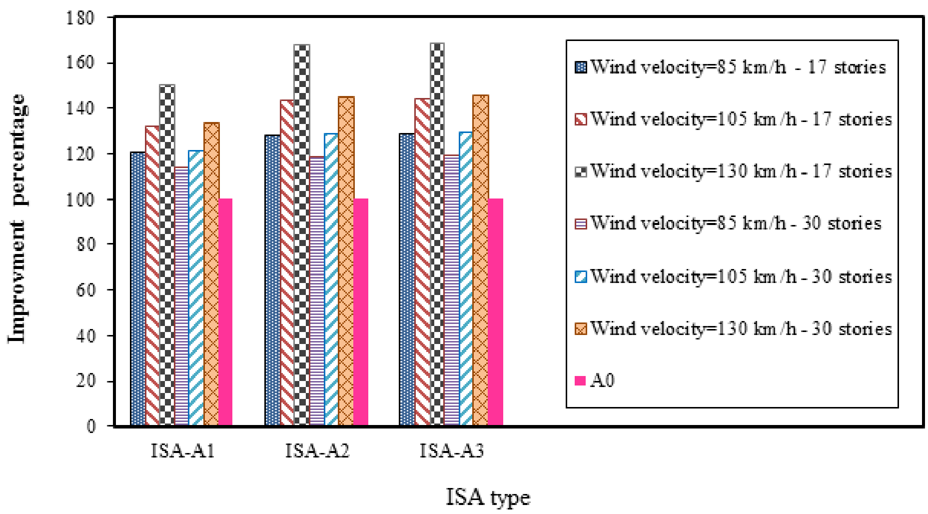


Figure 6. Percentage of improvement in stability safety factor.

As shown in Fig. 6, the safety factor of overall stability of the structures considering overturning movement is improved up to 80% by using ISA, and also the results show that ISA system in order to increasing this safety factor is more effective when a structure subjected to more fierce wind. From this figure it is noticeable that the trend of increasing safety factor of overturning at other airfoils is the same and ISA type A1 gives lower safety factor and both A2 and A3 work similar, whereas from Fig. 5, A3 work much better than A2 in order to controlling the uplift forces.

As it is shown in Fig. 6, the safety factor of overturning has been properly increased by employing ISA; also it is observed that the percentage of increasing of the safety factor of overturning at ISA type A2 is more than ISA type A1 and the most percentage of increasing of safety factor of overturning is related to ISA type A3; so accordingly, it could be received using an ISA with flap is more appropriate and the percentage of increasing of the safety factor of overturning for 17 stories building is more than 30 stories building; this the overturning safety factor PRI is increased with increasing wind velocity from 85 km/h to 130 km/h, thus unlike to prior case that is mentioned for uplift forces, higher wind velocity have better effect on; the percentage of increasing of the safety factor of overturning.

4.3 Effect of ISA on the lateral drift

Tables 7 and 8 show how adding ISA to a structure can effect on lateral drift, as well as Figs. 7-9. The results related to 17 stories building is captured in Fig. 7, it is clear when this structure is subject to a wind with velocity of 85 km/h, as it is shown in Table 7, the value of drift ratio at stories of 6 and 7 at four cases consist of A0 to A3 is respectively equal to 0.000226, 0.000213, 0.000208, 0.000207 and 0.000324, 0.000309, 0.000303, 0.000302 and the drift PRI also at these stories for A1 to A3 is respectively equal to 5.8, 8, 8.4, 4.6, 6.5, 6.8. It is noted that, there is cross section shift at stories of 6 and 7 thus it is observed a jump at the curve and again this jump has been occurred at stories 12 and 13 because of cross section shift. From Table 7 and Fig. 7-a it is extracted that the lateral drift PRI for ISA type A2 is more than ISA typeA1 and the most lateral drift PRI has been seen for ISA type A3; this trend follows in Figs. 7-b and Fig. 7-c for wind with velocity 105 km/h and 130 km/h, respectively.

Table 7: Lateral drift ratio (×10^4) for 17 stories structure under all wind cases with and without ISA

Story No.	Wind velocity = 85 km/h							Wind velocity = 105 km/h							Wind velocity = 130 km/h						
	A0	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**	**A0**	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**	**A0**	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**
1	1.6	1.6	0.0	1.6	0.0	1.6	0	2.4	2.4	0.0	2.4	0.0	2.4	0.41	3.7	3.7	0.3	3.7	0.3	3.7	0.54
2	2.3	2.3	0.9	2.3	1.3	2.3	1.75	3.5	3.5	1.1	3.5	1.4	3.4	1.71	5.4	5.3	1.1	5.3	1.5	5.3	1.68
3	2.4	2.3	2.1	2.3	3.0	2.3	3.39	3.6	3.5	2.2	3.5	3.1	3.5	3.33	5.5	5.4	2.2	5.4	2.9	5.3	3.27
4	2.3	2.2	3.4	2.2	4.3	2.2	4.74	3.5	3.4	3.4	3.4	4.5	3.4	4.8	5.4	5.3	3.3	5.2	4.6	5.2	4.97
5	2.3	2.2	4.8	2.1	6.6	2.1	7.05	3.5	3.3	4.6	3.2	6.4	3.2	6.94	5.3	5.1	4.7	5.0	6.2	4.9	6.79
6	2.3	2.1	5.8	2.1	8.0	2.1	8.41	3.5	3.3	5.8	3.2	8.1	3.2	8.41	5.3	5.0	6.0	4.9	8.1	4.8	8.51
7	3.2	3.1	4.6	3.0	6.5	3.0	6.79	5.0	4.7	4.8	4.6	6.5	4.6	7.07	7.6	7.2	4.7	7.1	6.3	7.1	6.99
8	3.7	3.5	5.2	3.4	6.8	3.4	7.36	5.6	5.3	5.0	5.2	6.8	5.2	7.32	8.6	8.2	5.0	8.0	6.8	8.0	7.34
9	3.5	3.3	6.3	3.2	8.3	3.2	9.14	5.3	5.0	6.4	4.9	8.4	4.9	9.18	8.2	7.7	6.2	7.5	8.3	7.4	9.05
10	3.2	3.0	8.1	2.9	10.6	2.9	11.5	4.9	4.5	7.9	4.4	10.6	4.4	11.4	7.5	6.9	8.0	6.7	10.5	6.7	11.4
11	2.9	2.6	10.0	2.5	13.4	2.5	14.4	4.4	4.0	10.1	3.9	13.3	3.8	14.4	6.8	6.1	10.1	5.9	13.4	5.8	14.4
12	2.6	2.3	12.5	2.2	16.7	2.2	17.9	4.0	3.5	12.5	3.4	16.5	3.3	17.7	6.2	5.4	12.5	5.1	16.6	5.1	17.7
13	3.1	2.8	11.5	2.7	15.3	2.6	16.6	4.8	4.2	11.5	4.1	15.3	4.0	16.7	7.3	6.5	11.6	6.2	15.3	6.1	16.8
14	2.8	2.4	15.4	2.2	20.1	2.2	22.2	4.3	3.6	15.3	3.4	20.0	3.3	22.1	6.5	5.5	15.3	5.2	20.2	5.1	22.1
15	2.2	1.7	22.2	1.6	29.4	1.5	31.7	3.4	2.6	22.5	2.4	29.3	2.3	32	5.2	4.0	22.4	3.7	29.3	3.5	32
16	1.6	1.1	35.2	0.9	45.7	0.8	49.4	2.5	1.6	34.8	1.3	45.7	1.3	49.4	3.8	2.5	35.1	2.1	45.6	1.9	49.6
17	1.1	0.4	59.6	0.2	78.0	0.2	83.5	1.7	0.7	59.6	0.4	78.3	0.3	83.7	2.6	1.0	59.6	0.6	78.4	0.4	83.9

Table 8: Lateral drift ratio (×10^4) for 30 stories structure under all wind cases with and without ISA

Story No.	Wind velocity = 85 km/h							Wind velocity = 105 km/h							Wind velocity = 130 km/h						
	A0	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**	**A0**	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**	**A0**	**A1**	**PRI**	**A2**	**PRI**	**A3**	**PRI**
1	2.1	2.1	0.0	2.1	0.0	2.1	0.0	3.3	3.3	0.0	3.3	0.3	3.3	0.3	5.0	5.02	0.0	5.02	0.0	5.0	0.2
2	3.6	3.6	0.3	3.6	0.3	3.5	0.6	5.5	5.5	0.2	5.4	0.5	5.4	0.5	8.4	8.36	0.4	8.35	0.5	8.3	0.6
3	4.0	4.0	0.5	3.9	0.8	3.9	1.0	6.1	6.1	0.7	6.0	1.0	6.0	1.0	9.4	9.29	0.7	9.27	1.0	9.3	1.2
4	4.1	4.1	1.0	4.1	1.5	4.1	1.5	6.3	6.3	1.1	6.2	1.7	6.2	1.7	9.7	9.61	1.0	9.57	1.4	9.6	1.6
5	4.2	4.1	1.4	4.1	1.9	4.1	2.1	6.5	6.4	1.4	6.3	2.2	6.3	2.2	9.9	9.74	1.5	9.69	2.0	9.7	2.2
6	4.2	4.2	1.7	4.1	2.4	4.1	2.6	6.5	6.4	1.8	6.3	2.8	6.3	2.8	10.0	9.81	1.8	9.74	2.5	9.7	2.7
7	4.3	4.2	2.1	4.1	3.0	4.1	3.3	6.6	6.4	2.1	6.3	3.4	6.4	3.2	10.1	9.83	2.3	9.75	3.1	9.7	3.3
8	4.3	4.2	2.6	4.1	3.5	4.1	3.7	6.6	6.4	2.7	6.3	4.1	6.3	3.9	10.1	9.84	2.7	9.75	3.6	9.7	3.9
9	4.3	4.2	3.0	4.2	4.1	4.2	4.4	6.7	6.5	3.0	6.4	4.5	6.4	4.4	10.2	9.91	2.9	9.8	4.0	9.8	4.3
10	4.5	4.4	3.3	4.3	4.4	4.3	4.9	6.9	6.7	3.3	6.6	4.9	6.6	4.8	10.6	10.29	3.2	10.17	4.3	10.1	4.7
11	6.2	6.0	2.6	6.0	3.5	6.0	3.9	9.5	9.3	2.5	9.2	3.9	9.2	3.8	14.6	14.22	2.5	14.09	3.4	14.0	3.8
12	7.3	7.2	2.5	7.1	3.3	7.1	3.7	11.3	11.0	2.4	10.9	3.6	10.9	3.6	17.3	16.84	2.4	16.7	3.2	16.6	3.6
13	7.5	7.3	2.7	7.2	3.6	7.2	4.0	11.5	11.2	2.7	11.1	4.0	11.1	4.0	17.7	17.19	2.7	17.02	3.6	17.0	4.0
14	7.4	7.2	3.1	7.1	4.2	7.1	4.6	11.4	11.0	3.1	10.8	4.7	10.8	4.6	17.4	16.86	3.0	16.67	4.1	16.6	4.5
15	7.2	6.9	3.5	6.8	4.7	6.8	5.2	11.0	10.6	3.5	10.5	5.3	10.5	5.2	16.9	16.31	3.5	16.11	4.7	16.0	5.1
16	6.9	6.7	4.0	6.6	5.5	6.5	5.9	10.7	10.2	4.1	10.0	6.1	10.0	5.9	16.3	15.68	4.0	15.46	5.4	15.4	5.8
17	6.7	6.4	4.6	6.3	6.3	6.2	6.7	10.3	9.8	4.6	9.6	6.8	9.6	6.6	15.7	15.02	4.6	14.77	6.2	14.7	6.6
18	6.4	6.1	5.1	6.0	7.0	5.9	7.5	9.9	9.4	5.3	9.1	7.8	9.1	7.5	15.1	14.34	5.2	14.07	6.9	14.0	7.5
19	6.2	5.8	5.8	5.7	7.9	5.7	8.4	9.5	8.9	5.8	8.7	8.8	8.7	8.4	14.5	13.68	5.8	13.39	7.8	13.3	8.4
20	6.0	5.6	6.5	5.5	8.8	5.4	9.3	9.2	8.6	6.5	8.3	9.7	8.4	9.2	14.1	13.19	6.4	12.88	8.6	12.8	9.2
21	6.7	6.3	6.1	6.1	8.2	6.1	9.0	10.3	9.6	6.1	9.3	9.2	9.4	8.9	15.7	14.76	6.2	14.44	8.2	14.3	8.9
22	6.7	6.2	6.7	6.1	9.0	6.0	9.7	10.3	9.6	6.7	9.3	9.9	9.3	9.7	15.8	14.7	6.7	14.35	8.9	14.2	9.7
23	6.3	5.8	7.9	5.7	10.5	5.6	11.3	9.7	8.9	7.8	8.6	11.5	8.6	11.2	14.9	13.69	7.8	13.32	10.3	13.2	11.2
24	5.8	5.3	9.3	5.1	12.2	5.1	13.2	9.0	8.1	9.2	7.8	13.5	7.8	13.2	13.7	12.47	9.2	12.06	12.2	11.9	13.1
25	5.3	4.8	10.9	4.6	14.4	4.5	15.6	8.2	7.3	10.9	6.9	16.0	6.9	15.5	12.6	11.18	10.9	10.74	14.4	10.6	15.5
26	4.8	4.2	13.1	4.0	17.2	3.9	18.5	7.4	6.5	13.0	6.0	19.0	6.0	18.5	11.4	9.88	13.0	9.41	17.1	9.3	18.4
27	4.3	3.6	15.8	3.4	20.9	3.4	22.3	6.6	5.6	15.7	5.1	22.8	5.2	22.1	10.1	8.56	15.6	8.06	20.5	7.9	22.1
28	3.8	3.1	19.0	2.8	25.1	2.8	26.9	5.8	4.7	18.9	4.2	27.6	4.3	26.8	8.9	7.24	18.9	6.71	24.9	6.6	26.7
29	3.3	2.5	23.4	2.3	30.7	2.2	32.8	5.1	3.9	23.1	3.4	33.8	3.4	32.6	7.8	5.96	23.2	5.39	30.5	5.2	32.7
30	2.9	2.1	28.8	1.8	37.8	1.7	40.3	4.4	3.2	28.5	2.6	41.4	2.7	39.8	6.8	4.85	28.4	4.24	37.4	4.1	39.7

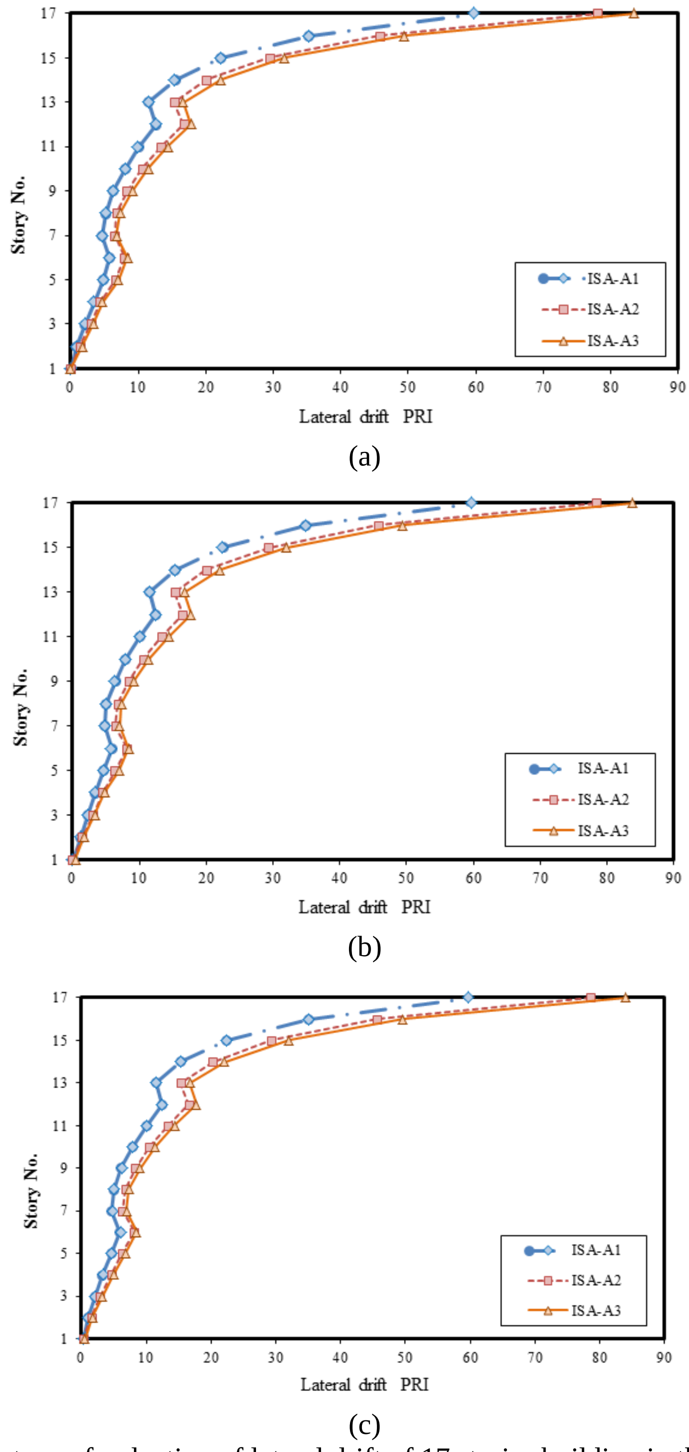
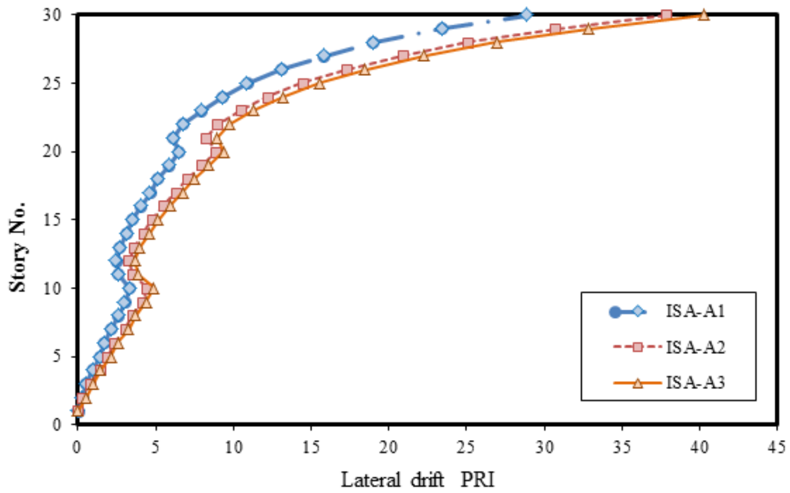
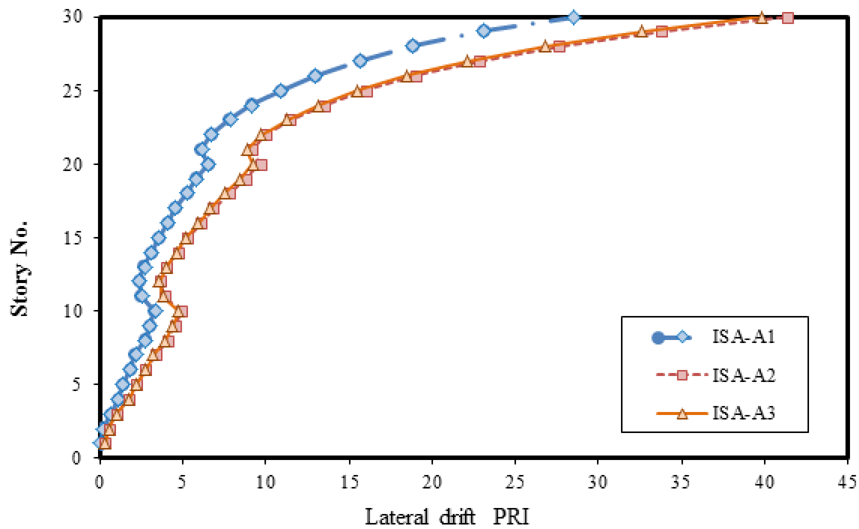


Figure 7. Percentage of reduction of lateral drift of 17 stories building in the presence of ISA respect to original structure; (a) under wind with velocity 85 km/h, (b) under wind with velocity 105 km/h and (c) under wind with velocity 130 km/h

The results for 30 stories structure is captured in Fig. 8 as well as Table 8. In Fig. 8-a the values of lateral drift PRI under a wind with velocity of 85 km/h is considered. According to Table 8, the value of drift ratio at stories of 10 and 11 at four cases consist of A0 to A3 is respectively equal to 0.000452, 0.000437, 0.000432, 0.00043 and 0.00062, 0.000604, 0.000598, 0.000596 and percentage of reduction drift ratio also at stories 10 and 11 for A1 to A3 is respectively equal to 3.3, 4.4, 4.9, 2.6, 3.5, 3.9. The observed jump at this figure is similar to what happened for 17 stories structure and discussed above. Also this jump is seen at stories of 20 and 21 has been occurred because of cross section shift.



(a)



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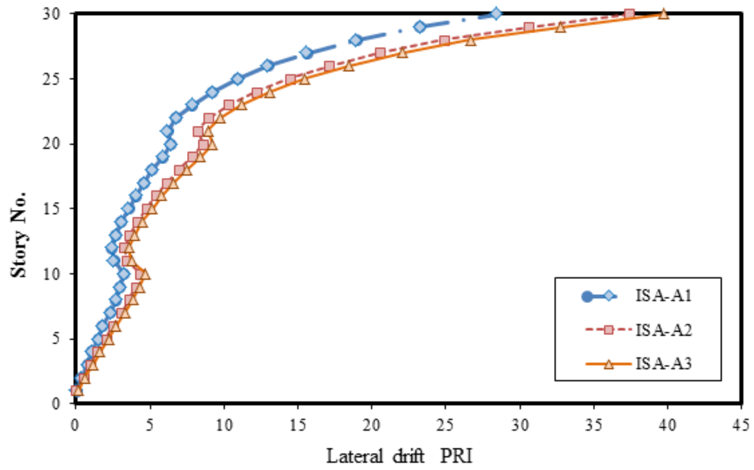

(c)

Figure 8. Percentage of reduction of lateral drift of 30 stories building in the presence of ISA respect to original structure; (a) under wind with velocity 85 km/h, (b) under wind with velocity 105 km/h and (c) under wind with velocity 130 km/h.

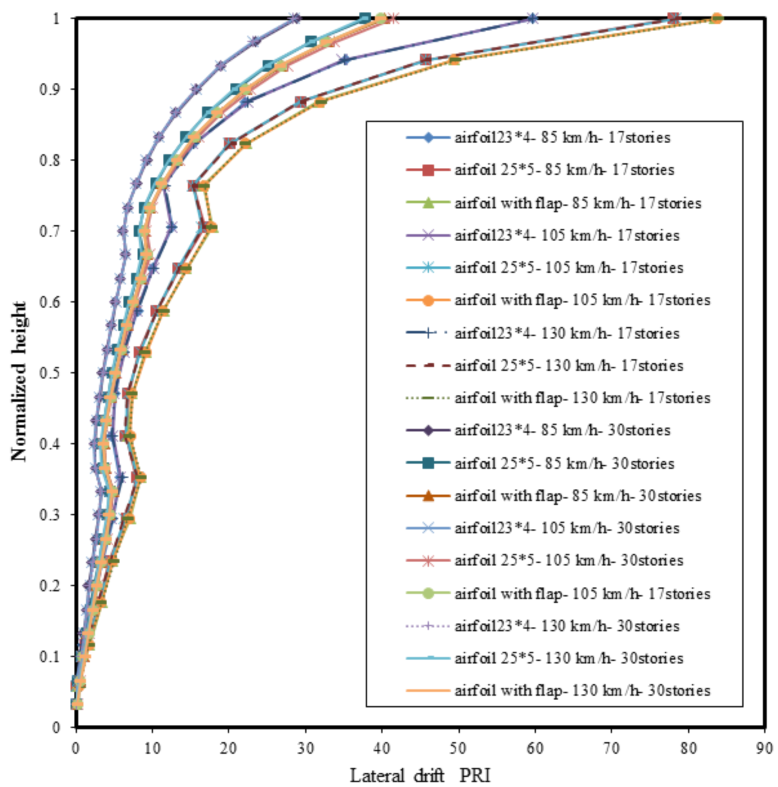

Figure 9. Distribution of lateral drift PRI for both structure under all wind condition and all ISA

The lateral drift PRI for the case that ISA type A2 is used has been observed larger than ISA type A1 and the most improvement in controlling the drift ratio is occurred when ISA type A3 is employed; this trend is also happened for the cases that the structure is subjected to wind with velocity 105 km/h and 130 km/h, as shown in Fig. 8-b and Fig. 8-c. Comparison between the results for 17 stories building (Table 7) and 30 stories building (Table 8) shows that ISA is more suitable for controlling the lateral drift in high-rise building rather than mid-rise one, however, ISA has been reduced the lateral drift in 17 stories structure but this reduction is limited up to 20%, whereas it is up to 55% in 30 stories structure.

According to Fig. 9, the drift ratio has been noticeably increased; also like to prior case, it is observed that the percentage of drift reduction at ISA type A2 is more than ISA type A1and the most percentage of drift PRI is happened when ISA type A3 has been used; therefore, in this case, it could be received using an airfoil with flap is more appropriate and again, the lateral drift PRI for the 17 stories building is more than 30 stories building, bet the percentage of drift reduction of both buildings is considerable and proper. Unlike to both cases, changing wind velocity has negligible effect on the percentage of drift reduction.

5. CONCLUSIONS

A novel instrument named Inverse Structural Airfoil (ISA) for improvement of structural performance for the building that is subjected to wind loads has been proposed. A couple of building with different height with for three types of ISA is analyzed under three wind cases, as well as related structures without ISA have been done. Results of this study have shown that using ISA could have significantly reduced parameters such as uplift forces, safety factor respect to overturning moment and lateral drift.

An ISA with larger size have better performance than similar ISA with small size and the best performance belong to airfoil with flap, because it produces the most negative lift force. Increasing the wind velocity causes increasing in the vertical and drag forces; the forces of drag and wind velocity are against of lift force, as a result it would be increased uplift and safety factor of overturning, however changing wind velocity has a negligible effects on lateral drift ratio improvement. The higher structure the higher wind velocity and consequently, it is increased the forces of lift and drag, but the more area of structure is affected wind force, thus along the elevation of the higher structure, reduction in trend of improving results is seen.

As a short result, it is obviously can said that using ISA at the top of a structure leads to improvement structural system and it is received that by ISA, we can reduce detrimental effects of wind of structures and use wind itself as an constructive parameter in order to forces and displacement due to wind.

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