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The slenderness effect on wind response of industrial reinforced concrete chimneys

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Abstract. There are several parameters affecting the response of industrial reinforced concrete (RC) chimneys, i.e., the severity of wind and earthquake loads acting to the structure, structural properties such as height and cross section of the chimney, the slenderness property of the structure etc. One of the most important parameter that should be considered while understanding the wind response of industrial RC chimneys is slenderness property. Although there is no certain definition for slenderness effect on these structures, some standards like ASCE-7 define slenderness from different aspects of the structural properties. In the first part of this study, general information about the definition of slenderness in the well-known standards and ten selected industrial RC chimneys are given. In the second part of the study, brief information about wind load standards that are used for calculating wind loads namely ACI 307/98, CICIND 2001, DIN 1056, TS 498 and Eurocode 1 is given. In the third part of the study, calculated wind loads for selected chimneys are represented. In the fourth part of this study, the internal forces obtained from load combinations that are applied to chimneys and some graphs presenting the effect of slenderness on chimneys are given. In the last part of the study, a conclusion and discussion part is taking place.

Keywords: slenderness; reinforced; concrete; chimney; wind; response

1. Introduction

Slenderness is one of the most important criteria that affect the behavior of structures that have massive heights and irregular shapes such as RC chimneys. These kinds of structures show different responses under different kinds of load combinations. This study deals with wind responses of selected slender and non-slender RC chimneys under selected wind loads by using different wind load standards. These standards are ACI 307/98 (ACI 1998), DIN 1056 (DIN 1984), CICIND 2001(CICIND 2001), TS 498(TSI 1997) and Eurocode 1(CEN 2004).

From literature survey, there are some of the studies dealing with industrial RC chimneys. Kareem and Hseih (1986) presented the reliability analysis of tall RC chimneys under wind loads. Tamura and Nishimura (1990) composed an elastic model of RC chimney for wind tunnel testing.

In the study, it was concluded that the material presented is available for the wind tunnel testing. Huang and Gould (2007) studied 3-D pushover analysis of a collapsed RC chimney. The real-time

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performance monitoring of tuned mass damper system for a 183m RC chimney before, during and after installation of tuned mass damper was studied (Brownjohn *et al.* 2010). Abdullah (2011) dealt with the effect of wind loads during the construction of the concrete towers. Design wind loads on RC chimneys which are affected from interference and influence of strikes by carrying out an experimental case study was dealt (John *et al.* 2011). The structural analysis of RC chimneys that are exposed to uncontrolled fire was studied (Vaziri *et al.* 2011). Zhang and Li (2011) dealt the analysis of a collapsed RC chimney located in Balco Power Plant in India. Wind and earthquake analysis of RC chimneys was studied to find the most critical loads for the design of chimney shell (Reddy *et al.* 2011). The wind load identification of a rectangular shaped concrete chimney from aero elastic wind tunnel test was studied (Hwang *et al.* 2011). The seismic performance of a RC chimney by considering long-term wind-action, corrosion, hot action, lower level of construction and lower design standards was studied (Yang *et al.* 2012). Karaca and Türkeli (2012) studied about the determination and comparison of wind loads for RC chimneys. The influence of model surface roughness on wind loads of the RC chimney by comparing the full-scale measurements and wind tunnel simulations was studied (Chen *et al.* 2013). It was stated in the study that a wind tunnel test of a scaled-down model and field measurement were effective methods for elucidating the aerodynamic behavior of a chimney under a wind load. Soil-structure interaction analysis of 300 meters tall RC chimney under along-wind load with different foundation types was dealt (Jayalekshmi *et al.* 2013). It is clear from literature survey that there are a few studies dealing with the effect of slenderness on the wind response of RC chimneys. Therefore, it is inevitable to make such a research study on the subject.

For this study, ten industrial RC chimneys were selected and wind loads according to important wind load standards were calculated. In Table 1, the important structural properties such as diameter at upper and lower heights of chimneys and heights of these selected chimneys were given.

Table 1 Structural properties of modeled RC chimneys

Chimney No	Height from ground (m)	Outer Diameter at Base (m)	Inner Diameter at Base (m)	Base Wall Thickness (m)	Outer Diameter at Top (m)	Inner Diameter at Top (m)	Top Wall Thickness (m)
1	75	7,500	6,500	0,500	4,000	3,600	0,200
2	80	8,000	7,000	0,500	4,500	4,100	0,200
3	85	8,500	7,500	0,500	5,000	4,600	0,200
4	90	9,000	8,000	0,500	5,500	5,100	0,200
5	95	9,500	8,500	0,500	6,000	5,600	0,200
6	100	10,000	9,000	0,500	6,500	6,100	0,200
7	105	10,500	9,500	0,500	7,000	6,600	0,200
8	110	11,000	9,900	0,550	7,500	7,060	0,220
9	115	11,500	10,400	0,550	8,000	7,560	0,220
10	120	12,000	10,800	0,600	8,500	7,980	0,260

All selected chimneys were assumed to be constructed from reinforced concrete whose unit mass, unit weight, the module of elasticity and Poisson ratio is 2,5493 kN.s^2/m^4, 25 kN/m^3, 30.000.000 kN/m^2 and 0,2, respectively. Heights of modeled chimneys were starting from 75 meters and increasing to 120 meters with 5 meters increments whose heights are 75, 80, 85, 90, 95, 100, 105, 110, 115 and 120 meters. All these chimneys were modeled from non-prismatic circle sectioned concrete bars by dividing the height to ten equal parts. For example, selected 75 meter chimney was constructed from ten bars whose heights were 7,5 meters. Two dimensional dynamic analyses of these selected chimneys were carried out by the help of Structural Analysis Program SAP2000 V.9 (Wilson 2000) and the SAP2000 model of 75 meters high chimney was shown in Fig. 1.

In order to perform and simplify the analysis, some assumptions were made such as all node points that concrete bars were joining to each other have three degree of freedoms namely 2 translational and 1 rotational except at the base. The base of modeled RC chimneys were assumed to be fixed to the ground and at the same time it was accepted as no ground movement occurs at the base of chimneys. Effects caused from seismic actions were not in the scope of this specific study. All modeled chimneys were accepted as constructed on open areas that have low vegetation and fewer obstacles. All chimneys were analyzed with the assumption that there are no other chimneys near or around modeled chimneys, therefore the interference effects of other chimneys or other structures were neglected. Moreover, chimneys were accepted as that they have no holes on their walls.

In this study, slenderness of the modeled RC chimneys was evaluated according to definition of slenderness given in the standard ASCE-7 (ASCE 2006) & AS/NZS1170.2 (Standards Australia Limited 2002). According to this definition, ***structures that have first mode natural frequency less than one are accepted as slender***. The first mode natural frequencies and periods of the modeled RC chimneys were given in Table 2. According to the definition given above, five of the modeled RC chimneys which have first mode natural frequencies less than one were accepted as slender.

The purpose of this study is to observe the change of internal forces from non-slender to slender RC chimneys and derive some discussions and conclusions about the results of the changes of these internal forces.

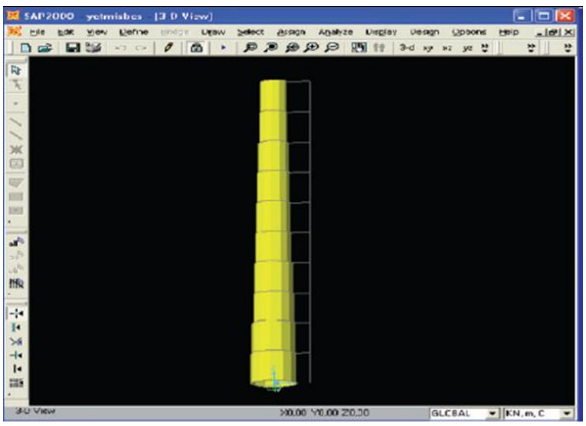

Fig. 1 75 meters high RC chimney modeled in SAP2000 (Wilson 2000)

Table 2 First mode natural period & frequencies of RC chimneys

Chimney No	**Chimney Height (m)**	**1st Mode Period (s)**	**1st Mode Frequency (Hz)**
1	75	0,777	1,287
2	80	0,830	1,206
3	85	0,882	1,134
4	90	0,935	1,070
5	95	0,987	1,013
6	100	1,039	0,962
7	105	1,091	0,916
8	110	1,166	0,858
9	115	1,219	0,821
10	120	1,320	0,758

2. Research significance

There are so many constructed industrial RC chimneys all over the world. Due to the fact that there is no specific definition for the slenderness of these tall structures, they are wholly accepted as slender which cause uneconomical and unsafe designs causing loss of property and lives. From literature survey, it is apparent that there are a few studies dealing with the wind response of industrial RC chimneys. Unfortunately, the authors still don’t meet any study dealing with the combined effect of wind and slenderness. Therefore, it is inevitable to make such a research study about the effect of slenderness on the wind responses of industrial RC chimneys. So many computer based computations were needed to display the effect of slenderness. It is believed by the authors that this study will enlighten the ways of designers and theoretician that are studying about the structural responses of industrial RC chimneys.

3. Brief information about the standards used in this study

In this part of the study, it is aimed to give only brief information about the standards used in the calculation of wind loads acting to modeled RC chimneys. All these cited wind loading standards are open to the use of the public. Therefore, there is no need to give detailed calculation procedures of the standards for the purpose of the volume limitation of the study.

3.1 ACI 307/98 (American Concrete Institute Committee) (ACI 1998)

Simplified dynamic analysis which is commonly accepted as equivalent static wind distribution is used for the calculation of wind loads according to ACI 307/98. In this standard, total wind load is assumed to be constituted by two parts namely the mean wind load part and fluctuating part.

Total wind load according to ACI 307/98 is shown in Eq. (1). The mean design speed found from reference design speed is used for the calculation of the mean part. Moreover, ACI 307/98 classifies all chimneys as IV category structures indicated in ANSI/ASCE 7-95 (ASCE 1996).

$$w(z) = w'(z) + \bar{w}(z) = \frac{4{,}5 \cdot z \cdot G_w \cdot M_{\bar{w}}(b)}{h^3} + C_{dr}(z) \cdot d(z) \cdot \bar{p}(z) \tag{1}$$

3.2 CICIND 2001 (Comité International des Cheminées Industrielles) (CICIND 2001)

In this standard, total wind on unit height is given by the summation of the mean wind load on unit height and the wind load according to instantaneous wind effect. Total wind load is shown in Eq. (2). The mean speed at height z which is found from basic wind speed as the hourly mean wind speed at 10 meters height from the ground at open terrain countries is used while calculating the mean wind load on unit height. Moreover, instantaneous wind parameter has an important role in the calculation of the wind according to instantaneous wind effect. Instantaneous wind parameter is the combination of some parameters namely maximum peak factor, turbulence intensity, theoretical turbulence parameter, and energy intensity spectrum and size reduction parameter.

$$w(z) = w_m(z) + w_g(z) = 0{,}5 \cdot \rho_a \cdot [v(z)]^2 \cdot C_D \cdot d(z) + \frac{3 \cdot (G-1)}{h^2} \cdot \frac{z}{h} \cdot \int_0^h w_m(z) \cdot z \cdot dz \tag{2}$$

3.3 DIN 1056 (Deutsches Institut für Normung) (DIN 1984)

The total resultant wind load which is shown in Eq. (3) is the combination of aerodynamic force parameter, dynamic pressure at height z and the effective surface area. Aerodynamic force parameter can be obtained from a table given in the standard depending on the section shape. According to the procedures given in the standard, dynamic pressure can be calculated from two different equations which one is suitable for the given condition. The calculation procedure of the effective surface area is explained in details on the figure provided in the standard.

$$W_i = C_{fi} \cdot q_i \cdot A_i \tag{3}$$

3.4 TS 498 (Design loads for buildings) (TSI 1997)

The total resultant wind load which is shown in Eq. (4) is the combination of aerodynamic load parameter, suction (wind pressure) and surface area affected. In this standard, a table that provides aerodynamic loads parameters for different type of structures. From this table, tower-type structures and the relevant information regarding tower-type structures can be chosen. Also wind speed and suction for different heights is provided on another table in the standard. The procedures used in this standard nearly same as used in DIN 1056. But there are some small changes in the calculation procedure.

$$W = C_f \cdot q \cdot A \qquad (kN) \tag{4}$$

3.5 Eurocode 1 (Actions on structures- general actions-part1-4: wind actions, 2004-01) (CEN 2004)

The most detailed and difficult standard for the users among the standards used for this study is Eurocode 1 standard. This standard deals with buildings and civil engineering works with heights up to 200 m. There are so many tables, formulas and figures in the wind load calculation procedure for the use of people using this standard in their calculations. In this standard, mean wind speed is not taken from a table or a chart. It is calculated from the basic wind velocity and the fundamental value of the basic wind velocity. Total wind load which is shown in Eq. (5) is the combination of structural factor, the force coefficient, peak velocity pressure and the reference area for the structure. This standard also deals with the turbulence intensity in the calculation of peak velocity pressure. The most difficult parameter to calculate in the wind load formula is the structural factor because it contains the resonant part and the resonant part has so many parameters in it. Another difference used in this standard is the use of Reynolds number in the determination of force parameter. Moreover, tables and figures are used for the selection of relevant information.

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \tag{5}$$

4. Calculated wind loads of modeled reinforced concrete chimneys according to the selected wind load standards

In this part of the study, calculated wind loads of modeled RC chimneys according to the selected wind load standards were given. All modeled RC chimneys were divided to ten sections along their heights and the calculated wind loads were represented in the tables by this way. The unit of loads given in these tables is kN/m. The calculated wind loads for modeled RC chimneys were shown in Tables 3-7. (Türkeli 2009)

Table 3 Total wind load results calculated for modeled R.C. chimneys according to ACI 307/98

Section No	**75 Mt. (kN/m)**	**80 Mt. (kN/m)**	**85 Mt. (kN/m)**	**90 Mt. (kN/m)**	**95 Mt. (kN/m)**	**100 Mt. (kN/m)**	**105 Mt. (kN/m)**	**110 Mt. (kN/m)**	**115 Mt. (kN/m)**	**120 Mt. (kN/m)**
0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
1	4,029	4,423	4,822	5,227	5,638	6,054	6,639	7,093	7,536	8,018
2	5,694	6,278	6,869	7,468	8,075	8,689	9,638	10,320	10,978	11,711
3	7,103	7,856	8,618	9,391	10,172	10,962	12,253	13,141	13,993	14,954
4	8,380	9,292	10,217	11,152	12,098	13,054	14,676	15,760	16,794	17,973
5	9,572	10,638	11,718	12,810	13,914	15,030	16,977	18,250	19,460	20,850
6	10,702	11,918	13,149	14,394	15,652	16,923	19,190	20,649	22,029	23,626
7	11,785	13,148	14,527	15,921	17,330	18,752	21,337	22,977	24,525	26,325
8	12,829	14,336	15,860	17,402	18,959	20,531	23,430	25,249	26,963	28,962
9	13,840	15,489	17,158	18,844	20,547	22,266	28,950	31,235	33,406	35,904
10	16,582	18,632	20,709	22,812	24,939	27,089	30,904	33,371	35,711	38,412

Table 4 Total wind load results calculated for modeled R.C. chimneys according to CICIND 2001

Section No	75 Mt. (kN/m)	80 Mt. (kN/m)	85 Mt. (kN/m)	90 Mt. (kN/m)	95 Mt. (kN/m)	100 Mt. (kN/m)	105 Mt. (kN/m)	110 Mt. (kN/m)	115 Mt. (kN/m)	120 Mt. (kN/m)
0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
1	5,444	5,926	6,417	6,916	7,423	7,938	8,460	8,990	9,526	10,069
2	6,372	6,958	7,555	8,163	8,780	9,407	10,043	10,689	11,342	12,006
3	7,018	7,688	8,371	9,065	9,771	10,488	11,215	11,955	12,702	13,467
4	7,688	8,449	9,224	10,012	10,813	11,625	12,450	13,294	14,140	15,017
5	8,531	9,407	10,297	11,203	12,122	13,054	13,999	14,972	15,942	16,962
6	9,635	10,664	11,708	12,768	13,843	14,933	16,035	17,181	18,311	19,522
7	11,049	12,281	13,530	14,797	16,079	17,376	18,688	20,062	21,404	22,870
8	12,785	14,284	15,803	17,340	18,894	20,464	22,049	23,721	25,341	27,140
9	14,821	16,665	18,530	20,415	22,319	24,240	26,177	28,231	30,207	32,431
10	17,101	19,381	21,684	24,008	26,353	28,716	31,097	33,631	36,055	38,813

Table 5 Total wind load results calculated for modeled R.C. chimneys according to DIN 1056

Section No	75 Mt. (kN/m)	80 Mt. (kN/m)	85 Mt. (kN/m)	90 Mt. (kN/m)	95 Mt. (kN/m)	100 Mt. (kN/m)	105 Mt. (kN/m)	110 Mt. (kN/m)	115 Mt. (kN/m)	120 Mt. (kN/m)
0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
1	5,209	5,730	6,266	6,814	7,375	7,948	8,533	9,138	9,747	10,386
2	6,459	7,107	7,772	8,451	9,145	9,854	10,576	11,322	12,072	12,859
3	7,076	7,803	8,548	9,309	10,086	10,879	11,687	12,521	13,359	14,239
4	7,393	8,177	8,980	9,800	10,639	11,494	12,365	13,263	14,166	15,114
5	7,526	8,355	9,203	10,071	10,957	11,861	13,671	14,684	15,700	16,765
6	7,533	8,398	9,931	10,898	11,884	12,889	13,912	14,966	16,023	17,130
7	7,964	8,919	9,896	10,895	11,913	12,951	14,007	15,094	16,184	17,324
8	7,786	8,766	9,770	10,795	11,841	12,905	13,988	15,102	16,220	17,387
9	7,542	8,544	9,570	10,618	11,686	12,773	13,879	15,015	16,155	17,344
10	7,244	8,265	9,310	10,376	11,464	12,570	13,694	14,849	16,008	17,214

Table 6 Total wind load results calculated for modeled R.C. chimneys according to TS 498

Section No	75 Mt. (kN/m)	80 Mt. (kN/m)	85 Mt. (kN/m)	90 Mt. (kN/m)	95 Mt. (kN/m)	100 Mt. (kN/m)	105 Mt. (kN/m)	110 Mt. (kN/m)	115 Mt. (kN/m)	120 Mt. (kN/m)
0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
1	5,743	6,135	6,527	11,437	12,085	12,733	13,381	14,029	14,677	15,325
2	9,040	9,688	10,336	10,984	11,632	12,280	17,596	18,478	19,360	20,242
3	11,687	12,569	13,451	14,333	15,215	16,097	16,979	17,861	18,743	19,625
4	11,069	11,951	12,833	13,715	14,597	15,479	16,361	17,243	18,125	19,007
5	10,452	11,334	12,216	13,098	13,980	14,862	15,744	16,626	17,508	18,390
6	9,834	10,716	11,598	12,480	13,362	14,244	15,126	16,008	16,890	17,772
7	9,217	10,099	10,981	11,863	12,745	13,627	14,509	15,391	16,273	17,155
8	8,600	9,482	10,364	11,246	12,128	13,010	13,892	14,774	15,656	16,538
9	7,982	8,864	9,746	10,628	11,510	12,392	13,274	14,156	18,039	19,097

10	7,365	8,247	9,129	10,011	10,893	11,775	15,182	16,240	17,298	18,356

Table 7 Total wind load results calculated for modeled R.C. chimneys according to Eurocode 1

Section No	75 Mt. (kN/m)	80 Mt. (kN/m)	85 Mt. (kN/m)	90 Mt. (kN/m)	95 Mt. (kN/m)	100 Mt. (kN/m)	105 Mt. (kN/m)	110 Mt. (kN/m)	115 Mt. (kN/m)	120 Mt. (kN/m)
0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
1	21,003	23,304	25,525	28,052	30,567	33,276	36,058	39,655	42,620	46,724
2	31,216	34,577	37,808	41,481	45,124	49,043	53,057	58,259	62,521	68,439
3	37,610	41,708	45,647	50,115	54,545	59,304	64,176	70,481	75,644	82,809
4	41,809	46,477	50,968	56,051	61,091	66,502	72,038	79,183	85,048	93,163
5	44,496	49,629	54,575	60,159	65,699	71,639	77,718	85,537	91,975	100,852
6	46,042	51,565	56,899	62,902	68,864	75,250	81,785	90,160	97,084	106,587
7	46,675	52,532	58,203	64,564	70,890	77,659	84,587	93,426	100,769	110,797
8	46,547	52,694	58,663	65,336	71,980	79,082	86,353	95,585	103,294	113,767
9	45,768	52,170	58,406	65,351	72,278	79,671	87,244	96,810	104,845	115,696
10	22,209	25,523	28,762	32,354	35,944	39,770	43,691	48,616	52,779	58,366

5. Internal forces of modeled RC chimneys obtained from load combinations that are applied and the effect of slenderness on modeled chimneys

In this part of the study, the internal forces of modeled RC chimneys obtained from load combinations that are applied to chimneys and some graphs representing the effect of slenderness on these modeled chimneys were given. There were three load combinations used in the analysis of RC chimneys which were taken from Turkish Standard 2000 (TSI 2000). The load combinations used for the analysis of RC chimneys are as follows

$K_1 = W$,
$K_2 = G + 1,30 x (Q) + 1,30 x (W)$,
$K_3 = 0,90 x (G) + 1,30 x (W)$. (TSI 2000)

In these combinations shown, W is representing wind load, G is representing dead load and Q is representing live load on the structure. In this study, it was assumed that there was no live load on the modeled RC chimneys. Therefore, live load part of the combination K_2 was zero. All of these load combinations were applied to modeled RC chimneys in global X-direction and some internal forces namely normal forces, shear forces and moments were obtained by the help of the structural analysis program SAP2000. It is a waste of time to show all of these internal forces in this part of the study. Therefore, only the internal forces needed to determine the effect of slenderness on the modeled RC chimneys were shown. The internal forces needed to determine the effect of slenderness on the modeled RC chimneys were shown in Table 8-11. In these tables, only the internal forces at the bottom of the modeled RC chimneys were represented. Moreover, in order to determine the effect of slenderness, the percentage differences of these bottom internal forces among the modeled RC chimneys were shown in these tables. This percentage differences were calculated by subtracting the two internal forces from each other, dividing the subtraction to the first value and multiplying by one hundred. For example, shear difference %18,86 for ACI 307/98 in Table 8 was found by this way

$$\textit{The Percentage Shear Difference} = \left[\frac{896kN - 754kN}{754kN}\right] * 100 = 18{,}86\%$$

Then, the graphs that were used for the evaluation of the effect of slenderness on these modeled chimneys were constituted by using the percentage differences tabulated in Tables 8-11. The units of these internal forces are kN for shear forces and kN.m for moments.

Table 8 Shear forces on the bottom of the modeled RC chimneys and the percentage differences of this internal force (K_1 load combination) among the modeled R.C. chimneys

Chimney Height (m)	**ACI 307-98**		**Eurocode-1**		**DIN 1056**		**TS 498**		**CICIND 2001**	
	Shear forces at the bottom of R.C. x-axis (kN)	**% Shear Diff.**	**Shear forces at the bottom of R.C. x-axis (kN)**	**% Shear Diff.**	**Shear forces at the bottom of R.C. x-axis (kN)**	**% Shear Diff.**	**Shear forces at the bottom of R.C. x-axis (kN)**	**% Shear Diff.**	**Shear forces at the bottom of R.C. x-axis (kN)**	**% Shear Diff.**
75	754	—	2875	—	538	—	682	—	753	—
80	896	18,86	3441	19,69	641	18,44	793	16,16	894	18,62
85	1051	17,29	4041	17,43	759	16,30	911	14,93	1047	17,11
90	1219	15,96	4737	17,22	882	15,21	1078	18,34	1212	15,83
95	1400	14,83	5481	15,71	1016	14,25	1217	12,91	1391	14,73
100	1594	13,86	6312	15,15	1161	14,21	1365	12,12	1582	13,78
105	1932	21,24	7210	14,23	1326	12,76	1596	16,96	1787	12,94
110	2178	12,76	8335	15,59	1495	12,76	1769	10,80	2010	12,46
115	2431	11,59	9391	12,67	1675	11,99	1985	12,19	2242	11,55
120	2721	11,92	10766	14,65	1869	11,60	2178	9,75	2500	11,48

Table 9 Moments on the bottom of the modeled RC chimneys and the percentage differences of this internal force (K_1 load combination) among the modeled R.C. chimneys

Chimney Height (m)	**ACI 307-98**		**Eurocode-1**		**DIN 1056**		**TS 498**		**CICIND 2001**	
	Moments at the bottom of R.C. about y-axis (kN.m)	**Moment Diff.**	**Moments at the bottom of R.C. about y-axis (kN.m)**	**% Moment Diff.**	**Moments at the bottom of R.C. about y-axis (kN.m)**	**% Moment Diff.**	**Moments at the bottom of R.C. about y-axis (kN.m)**	**% Moment Diff.**	**Moments at the bottom of R.C. about y-axis (kN.m)**	**% Moment Diff.**
75	34176	—	112705	—	21051	—	25185	—	33990	—
80	43447	27,13	144638	28,33	26899	26,51	31439	24,83	43258	27,27
85	54261	24,89	181239	25,30	34031	23,66	38635	22,89	54076	25,01
90	66746	23,01	225741	24,55	42081	22,03	47021	21,71	66572	23,11
95	81027	21,40	276527	22,50	51353	20,62	56329	19,79	80875	21,48
100	97234	20,00	336039	21,52	61940	20,09	66777	18,55	97113	20,08
105	125221	28,78	403938	20,21	74384	18,38	81849	22,57	115416	18,85
110	148101	18,27	490080	21,33	88056	18,38	95354	16,50	136317	18,11
115	172926	16,76	578198	17,98	103284	17,29	113631	19,17	159221	16,80
120	202185	16,92	692712	19,81	120471	16,64	130516	14,86	185697	16,63

Table 10 Shear forces on the bottom of the modeled RC chimneys and the percentage differences of this internal force (K_2 and K_3 load combinations) among the modeled R.C. chimneys

Chimney Height (m)	ACI 307-98		Eurocode-1		DIN 1056		TS 498		CICIND 2001	
	Shear forces at the bottom of R.C. x-axis (kN)	% Shear Diff.	Shear forces at the bottom of R.C. x-axis (kN)	% Shear Diff.	Shear forces at the bottom of R.C. x-axis (kN)	% Shear Diff.	Shear forces at the bottom of R.C. x-axis (kN)	% Shear Diff.	Shear forces at the bottom of R.C. x-axis (kN)	% Shear Diff.
75	980	—	3738	—	699	—	887	—	979	—
80	1165	18,86	4474	19,69	833	18,44	1030	16,16	1162	18,62
85	1366	17,29	5254	17,43	986	16,30	1184	14,93	1360	17,11
90	1584	15,96	6158	17,22	1147	15,21	1402	18,34	1576	15,83
95	1819	14,83	7126	15,71	1321	14,25	1583	12,91	1808	14,73
100	2072	13,86	8206	15,15	1510	14,21	1774	12,12	2057	13,78
105	2512	21,24	9374	14,23	1724	12,76	2075	16,96	2323	12,94
110	2832	12,76	10835	15,59	1944	12,76	2300	10,80	2613	12,46
115	3160	11,59	12208	12,67	2177	11,99	2580	12,19	2915	11,55
120	3537	11,92	13996	14,65	2430	11,60	2832	9,75	3249	11,48

Table 11 Moments on the bottom of the modeled RC chimneys and the percentage differences of this internal force (K_2 and K_3 load combinations) among the modeled R.C. chimneys

Chimney Height (m)	ACI 307-98		Eurocode-1		DIN 1056		TS 498		CICIND 2001	
	Moments at the bottom of R.C. about y-axis (kN.m)	% Moment Diff.	Moments at the bottom of R.C. about y-axis (kN.m)	% Moment Diff.	Moments at the bottom of R.C. about y-axis (kN.m)	% Moment Diff.	Moments at the bottom of R.C. about y-axis (kN.m)	% Moment Diff.	Moments at the bottom of R.C. about y-axis (kN.m)	% Moment Diff.
75	44428	—	146517	—	27367	—	32741	—	44186	—
80	56481	27,13	188030	28,33	34969	26,51	40871	24,83	56235	27,27
85	70540	24,89	235610	25,30	44240	23,66	50226	22,89	70298	25,01
90	86770	23,01	293463	24,55	54705	22,03	61127	21,71	86544	23,11
95	105336	21,40	359485	22,50	66759	20,62	73227	19,79	105138	21,48
100	126405	20,00	436850	21,52	80522	20,09	86810	18,55	126247	20,08
105	162788	28,78	525120	20,21	96699	18,38	106403	22,57	150041	18,85
110	192531	18,27	637104	21,33	114473	18,38	123960	16,50	177212	18,11
115	224803	16,76	751657	17,98	134269	17,29	147720	19,17	206987	16,80
120	262840	16,92	900526	19,81	156612	16,64	169671	14,86	241406	16,63

In order to evaluate the effect of slenderness on the modeled RC chimneys, all the percentage difference values that were tabulated in Table 8-11 were plotted on graphs and some conclusions were drawn from these graphs. The plotted percentage difference values were shown in Figs. 2-5. In these graphs, X-axis shows the height of chimneys and Y-axis shows percentage difference values (Türkeli 2009).

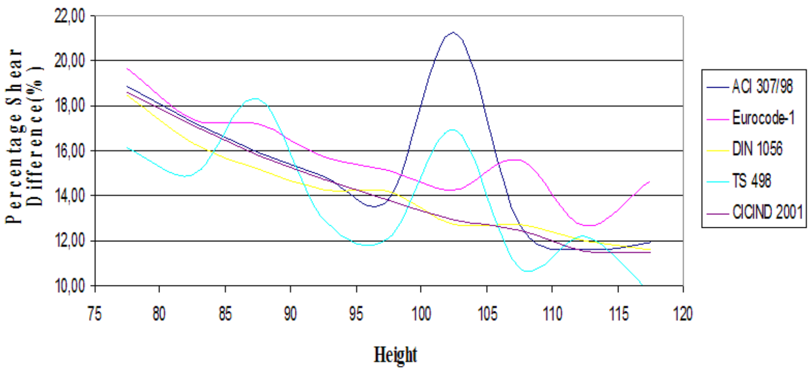

Fig. 2 The effect of slenderness on shear forces of modeled R.C. chimneys (K_1 load combination)

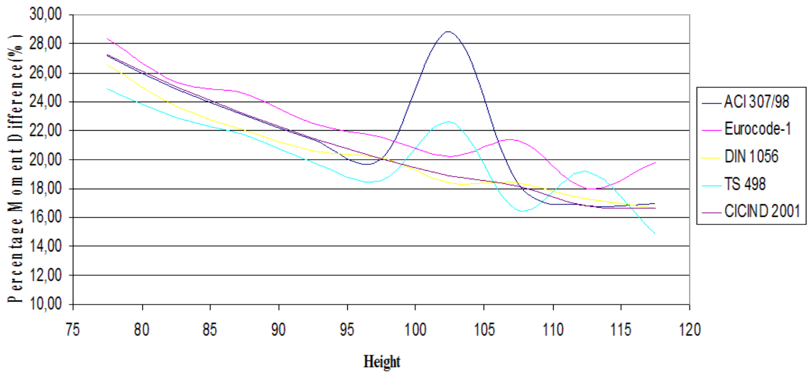

Fig. 3 The effect of slenderness on moments of modeled R.C. chimneys (K_1 load combination)

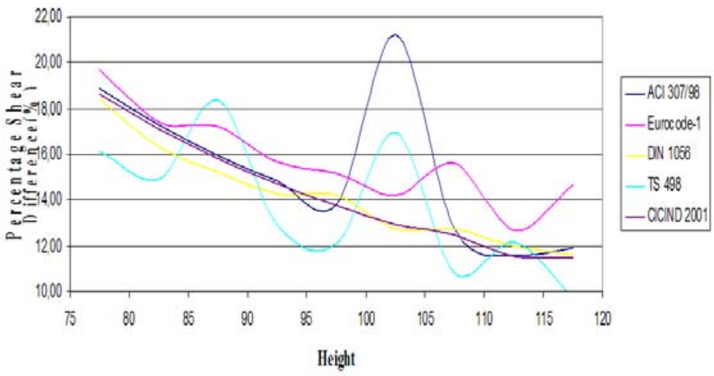

Fig. 4 The effect of slenderness on shear forces of modeled R.C. chimneys (K_2 and K_3 load)

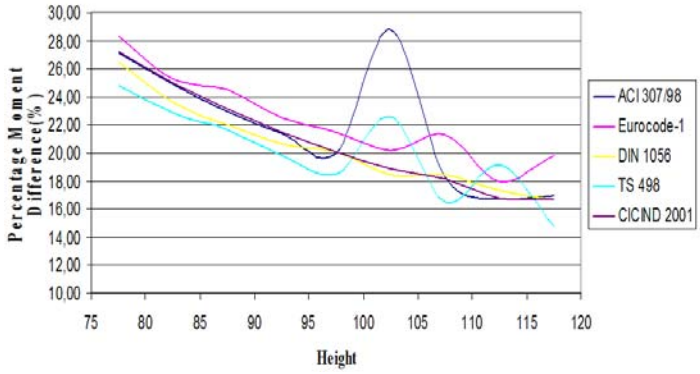

Fig. 5 The effect of slenderness on moments of modeled R.C. chimneys (K_2 and K_3 load combinations)

6. Conclusions

In this study, the effect of slenderness of industrial RC chimneys was investigated by using the percentage changes of internal forces for the ten modeled RC chimneys in an accepted structural analysis program, SAP2000. The slenderness definition given in the cited standards were used for the slenderness evaluation of the modeled chimneys. This definition is selected due to the fact that it contains the dynamic properties of the structures which are the bases of dynamic structural analysis.

The evaluation of the effect of slenderness on RC chimneys was made according to the graphs constituted from the percentage differences of internal forces obtained in the structural analysis. According to the interpretation of the graphical results, for the majority of the wind loading standards used in this study, it is believed that slenderness plays an important role on the sudden percentage difference increments of internal forces of RC chimneys especially on the transition zone from non-slender to slender around 95-110 meters. These sudden increments explicitly seen on the graphs constituted from percentage differences of internal forces obtained from wind load standards namely ACI 307/98, TS 498 and Eurocode 1. Moreover, it is thought that these cited standards reflect the effect of slenderness on the wind response of modeled RC chimneys. Also, from the graphs showing the percentage differences of internal forces of RC chimneys according to load combinations K_1, K_2 and K_3 explained, it is easily seen that there is approximately 8% increment in shear force differences according to ACI 307/98, 5% increment according to TS 498 and 2% increment according to Eurocode 1 on the transition zone from non-slender to slender around 95-110 meters. By the same way, according to graphs constituted from load combinations K_1, K_2 and K_3 explained, it is easily seen that there is approximately 10% increment in moment differences according to ACI 307/98, 4% increment according to TS 498 and 1% increment according to Eurocode 1 on the transition zone from non-slender to slender around 95-110 meters. The standard that has the greatest percentage difference increment in internal forces (both shear and moment) is ACI 307/98.

In the light of the findings of this study, it is thought that slenderness (evaluated according to the cited definition) affects the internal forces of industrial RC chimneys and causes them to increase rapidly. These rapid increases can cause industrial RC chimneys collapse in a brittle manner without showing any ductile response. Therefore, in order to make reliable and economical projects, it is important to consider the effect of slenderness on wind responses of slender industrial RC chimneys.

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