NATURAL PERIOD OF STEEL CHIMNEYS

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Abstract. *Using the mechanical model of flange bolted joints, parametric study has been conducted to investigate influence of joint stiffness on the behaviour of such structures as steel chimneys. Particularly, it was investigated the influence of the stiffness of flange bolted joints on the natural period of cantilevered steel chimneys. Based on results of the investigation, the following conclusions were stated: natural period of steel chimney T_1 increases if the number of joints increases and if the stiffness of joint decreases; when non-preloaded joints are used, the change of natural period is up to 30% for steel cantilevered chimneys. When preloaded joints are used, the change of natural period is small and can be neglected.*

1 INTRODUCTION

Steel chimneys are sensitive to dynamic wind action. In codes of many countries, to obtain wind loading it is necessary to know natural period of these structures, e.g. [1], [2]. Also in Eurocode 1-1-4 [3] natural period is required to reach structural factor $c_s c_d$ needed for wind loading. Natural period of the structure can be obtained by few methods: by experimental measure, using modal analysis, or by simplified equation. From the practical point of view, for wind loading assessment it is acceptable to use simplified methods.

In the paper, influence of the stiffness of flange bolted joints between segments on the main dynamic characteristics of chimney, i.e. natural period, has been analysed. Method of including influence of stiffness of flange bolted joints between segments in simplified equations is also proposed.

2 METHODS OF CALCULATION OF NATURAL PERIOD OF STEEL CHIMNEYS

Actual natural period of existing chimney can be easy reached at site by measurement of the time of selected number of cycles at vibrating chimney. Such measurement is executed during assessment of technical state of existing chimneys. For design aim, analytical or numerical methods are employed.

In Polish code [1] many practically useful simple formulas for assessment of natural period of steel chimneys are included. For the most simple structures as cantilevered chimney, natural period can be calculated as:

$$T_1 = 0{,}001\frac{H^2}{D} \tag{1}$$

where:

H – height of the chimney, D – diameter of chimney shell.

Simplified formulas were created on the basis of large number of site measurements of existing chimneys. Measurements were done during routine assessments of technical state of existing chimney executed in Poland in 80-ties. In these formulas many parameters, as stiffness of bolted connection in flanged joints between segments and in chimney basis were neglected.

Nowadays, most often modal analysis allowable in computer packages is used to obtain natural period of any structures.

3 ANALYSIS OF NATURAL PERIOD OF STEEL CHIMNEYS

The following types of chimneys were analysed:

- cantilevered chimney (fig. 1a),
- guyed chimney (fig. 1b),
- supported at intermediate level chimney (fig. 1c).

Influence of the stiffness of flanged joints between segments on the main dynamic characteristics of chimney, i.e. natural period, were analysed. Structural shell of chimneys was modelled using beam elements. Flange bolted connections (fig.2) were modelled as semi-rigid joints of linear stiffness characteristics. Initial stiffness of these joints applied in analysis was calculated with application of mechanical model of joint (fig. 3). Applied component method allows to reach formula for initial stiffness given by eq. (2). Detailed description of mechanical model of flanged joint was presented in [4].

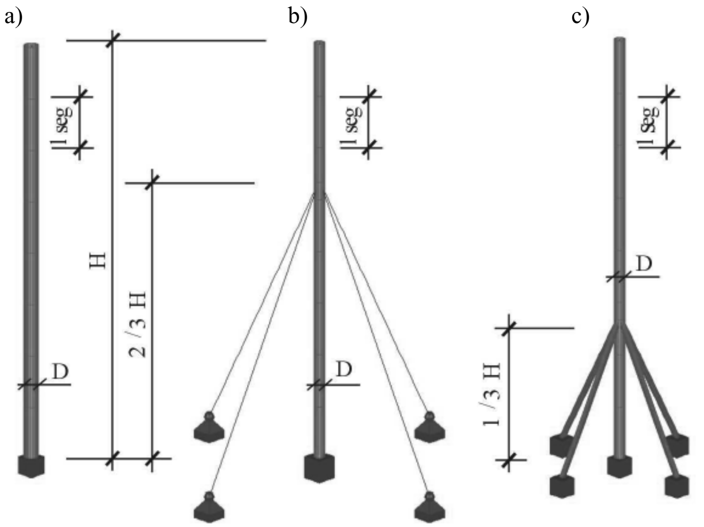


Fig. 1 Chimneys considered in the analysis

$$S_{j,ini} = k_t \cdot [(r+a)^2 + 2\sum_{1}^{n}(r \cdot cos(n\delta)+a)^2] + k_c \cdot [(r-a)^2 + 2\sum_{1}^{i}(r \cdot cos(i\delta)-a)^2] \qquad (2)$$

where: $S_{j,ini}$ – initial stiffness of joint, k_t (k_c) – stiffness of tension (compression) component, r – radius of the shell, a – distance between the neutral axis and centre of the joint, n (i) – number of components on tension (compression) side, δ - angle between Y axis and line coming through *i* component.

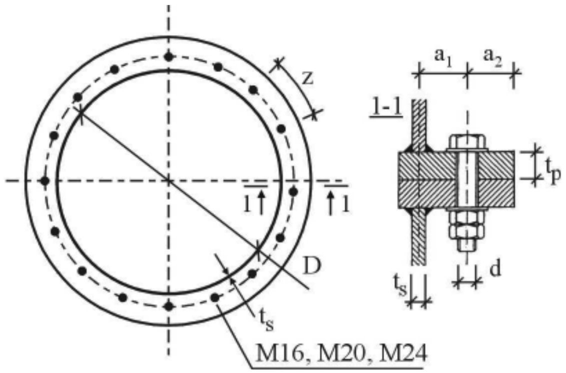


Fig. 2 Flanged bolted connection applied in the analysis

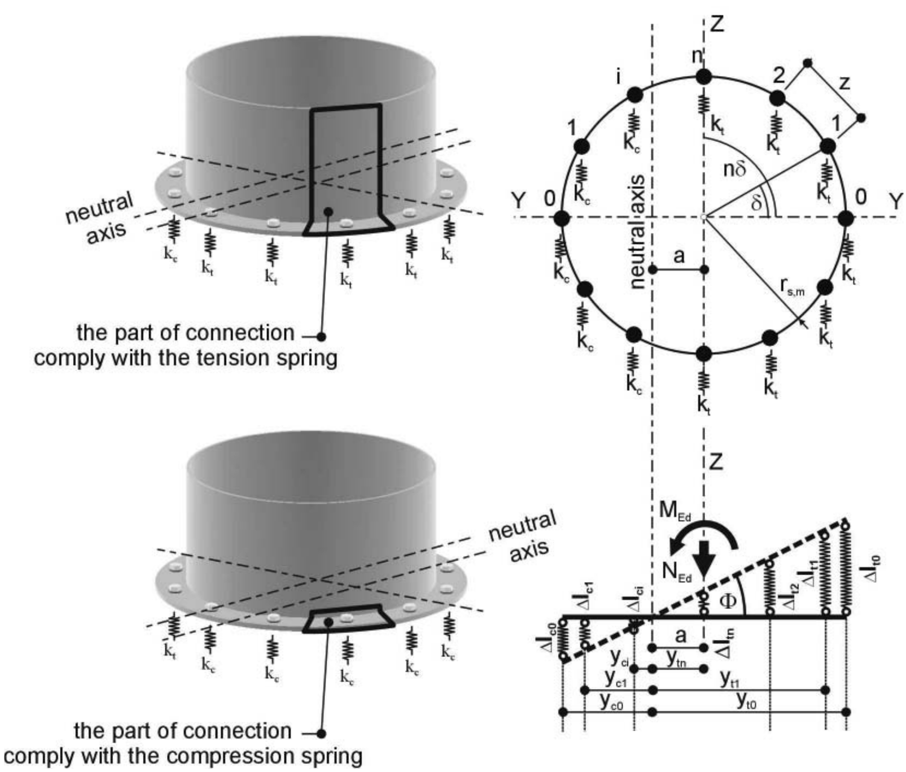


Fig. 3. Mechanical model of flange bolted connection between segments

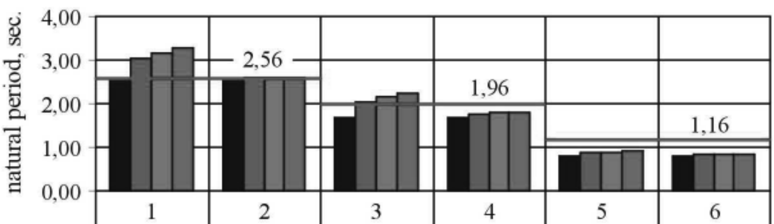
Calculation of natural period were provided by computer software Robot Structural Analysis 2009. In the analysis, the following range of geometrical parameters were chosen:

- for cantilevered chimneys:
    - slenderness of structural shell: H/D = 40,
    - shell diameter D: 0,8 to 1,6 m,
    - height of the chimney H was calculated as a product of diameter D and slenderness.
- guyed chimneys and chimneys supported at intermediate level:
    - slenderness of shell: H/D = 50,
    - shell diameter: 0,8 to 1,2 m,
    - height of the chimney H was calculated as a product of diameter D and slenderness,
    - level of additional support was taken as 2/3 H for guyed chimneys and 1/3H for stiff support.

First, influence of assembly bolted joints on chimney behaviour were investigated. Length of chimney segments l_{seg} was taken as 6 m, and number of connections n_i comes from segment length and chimney height H. Geometrical dimensions of connection used in the analysis were shown in fig. 2. Thickness of the end plate was taken as t_p=16 mm, bolt diameter d = 20 mm, distance from shell to bolt axis a_1=1,5 d, distance from bolt axis to plate edge a_2=1,5 d, bolt spacing 4d, 7d and 10d. Non preloaded connection with grade 5.8 bolts as well as preloaded with grade 10.9 bolts were analyzed. Results of analysis can be seen in fig. 4. Horizontal line shows value of natural period obtained by simplified formulas from [1]. Detailed results of more complex analysis can be found in [5].

The following conclusions can be drawn:

- in case of preloaded joints, change in natural period is small and can be neglected in the design,
- for guyed chimneys with non-preloaded joints, stiffness of the assembly connection do not influence on natural period,
- for cantilevered and supported at intermediate level chimneys with non-preloaded bolts in connections, change in natural period can reach even 30 %.



	1	2	3	4	5	6
$S_{j,ini}$=inf.	2,56	2,56	1,68	1,68	0,82	0,82
z=4d	3,03	2,60	2,03	1,76	0,89	0,85
z=7d	3,17	2,61	2,15	1,79	0,90	0,85
z=10d	3,28	2,62	2,25	1,81	0,91	0,86

Fig. 4. Natural period of steel chimneys: 1 - cantilevered chimneys, non-preloaded joints, 2 - cantilevered chimneys, preloaded joints, 3 – supported at intermediate level chimneys, non-preloaded joints, 4 – supported at intermediate level chimneys, preloaded joints, 5 – guyed chimneys, non-preloaded joints, 6 – guyed chimneys, preloaded joints.

4 INFLUENCE OF INITIAL STIFFNESS OF FLANGED BOLTED JOINTS ON NATURAL PERIOD OF CANTILEVERED CHIMNEYS.

To the further analysis, cantilevered chimneys with non-preloaded bolts in connections were chosen. In the analysis the following assumptions were establish:

- constant thickness of chimney shell taken as 12 mm,
- the same joints type: M20 bolts grade 5.8.

Changeable parameters were:

- diameter D of shell: 0,8, 1,2 and 1,6 m,
- shell slenderness H/D: 20, 30, 40. In relation to slenderness change also height of chimney H was changed,
- number of bolted joints in relation to segment length l_{seg} = 6, 9, 12 and 15 m,
- stiffness of flanged joints $S_{j,ini}$ calculated for geometrical parameters: thickness of flanged plate 16 and 32 mm, distance form bolt axis to plate edge a_2 1,5d and 3d, bolt spacing 4d, 7d and 10d. Values of joint stiffness including in analysis were collected in table 1.

Natural period was calculated with and without taking into consideration presence of bolted joints. Results are presented in tables 2 to 4, where n_j – number of joints.

Table 1. Initial stiffness of non-preloaded flanged connections (x10^6 kNm/rad).

a_2	D=0,8m				D=1,2m				D=1,6m			
	t_p=16mm			t_p=32	t_p=16mm			t_p=32	t_p=16mm			t_p=32
	z=4d	z=7d	z=10d	z=4d	z=4d	z=7d	z=10d	z=4d	z=4d	z=7d	z=10d	z=4d
1,5	0,4	0,3	0,2	0,4	1,3	1,0	0,8	1,6	3,0	2,2	1,9	3,5
3,0	0,5	0,4	0,3	0,6	1,4	1,1	0,9	2,2	3,6	2,5	2,0	5,2

Table 2. Natural period of chimneys of slenderness H/D=20.

$S_{i,ini}$ x10^6 kNm/rad	slenderness H/D = 20									
	H =16m; D = 0,8m			H =24m; D = 1,2m				H =32m; D = 1,6m			
	n_j=0	n_j=1	n_j=2	n_j=0	n_j=1	n_j=2	n_j=3	n_j=0	n_j=2	n_j=3	n_j=5
0,2		0,33	0,37		0,50	0,53	0,58		0,69	0,72	0,79
0,3		0,33	0,36		0,50	0,52	0,56		0,68	0,71	0,76
0,4		0,33	0,35		0,49	0,51	0,54		0,67	0,69	0,74
0,6		0,33	0,34		0,49	0,50	0,52		0,66	0,67	0,70
∞	0,32			0,48				0,64			

Table 3. Natural period of chimneys of slenderness H/D=30.

$S_{i,ini}$ x10^6 kNm/rad	slenderness H/D = 30											
	H =24m; D = 0,8m				H =36m; D = 1,2m				H =48m; D = 1,6m			
	n_j=0	n_j=1	n_j=2	n_j=3	n_j=0	n_j=2	n_j=3	n_j=5	n_j=0	n_j=3	n_j=5	n_j=7
0,8		0,70	0,74	0,81		1,17	1,23	1,34		1,59	1,67	1,82
0,9		0,69	0,71	0,77		1,15	1,20	1,30		1,56	1,63	1,76
1,3		0,68	0,70	0,74		1,14	1,17	1,25		1,53	1,59	1,69
2,2		0,68	0,69	0,72		1,11	1,14	1,18		1,49	1,53	1,59
∞	0,67				1,08				1,44			

Table 4. Natural period of chimneys of slenderness H/D=40.

$S_{j,ini}$ x10^6 kNm/rad	slenderness H/D = 40											
	H =24m; D = 0,8m				H =36m; D = 1,2m				H =48m; D = 1,6m			
	n_j=0	n_j=1	n_j=2	n_j=3	n_j=0	n_j=2	n_j=3	n_j=5	n_j=0	n_j=3	n_j=5	n_j=7
1,9		1,40	1,48	1,63		2,12	2,23	2,43		2,89	3,01	3,28
2,2		1,36	1,42	1,53		2,08	2,17	2,34		2,83	2,94	3,17
3,0		1,34	1,39	1,47		2,05	2,12	2,25		2,77	2,85	3,03
5,2		1,33	1,35	1,41		2,00	2,04	2,12		2,68	2,73	2,84
∞	1,29				1,92				2,56			

On the basis of the results review it can be concluded that natural period of cantilevered chimneys increases with the increase of number of bolted joints and when the joint stiffness decrease. Differences with relation to chimneys without bolted joints is up to 20% for chimneys of H/D=20, 25% for chimneys of H/D=30, and up to 30% for chimneys of H/D=40.

5 PROPOSAL FOR INCLUDING FLANGED JOINT STIFFNESS IN CALCULATION OF NATURAL PERIOD OF CHIMNEYS

Simply method allowing including stiffness of flanged connections in preliminary calculation of natural period of steel cantilevered chimneys has been proposed. Formula (1) was modify by adding component ΔT_1, which takes into account number n_j and stiffness of connections $S_{j,ini}$ (eq. 3).

$$T_1 = 0{,}001\frac{H^2}{D} + \Delta T_1 \tag{3}$$

Component ΔT_1 can be read from fig. 5, in relation to number of bolted connections n_j and parameter η, which is obtained form eq. (4)

$$\eta_i = \frac{S_{j,109}}{S_{j,ini}} \tag{4}$$

where:

$S_{j,109}$ – reference stiffness of preloaded joint, calculated for the following data: bolts M20 grade 10.9, spacing of bolts 4d, thickness of end plate t_p=32mm, distance form edge to bolt axis a_2=3,0d. Reference stiffness can be taken as 7500000 kNm/rad, 3200000 kNm/rad, 900000 kNm/rad, for chimneys of diameter 1,6 m, 1,2 m and 0,8 m relatively.

$S_{j,ini}$ – initial stiffness of non-preloaded joints, obtained with the use of mechanical model, or estimated using data from table 1, taking into account geometrical parameters of joint.

The coefficient η_i was calculated as a ratio of stiffness $S_{j,109}$ and $S_{j,ini}$. The influence of stiffness of flange bolted joints on natural period increases when the value of this coefficient increases.

The parameter ΔT_1 can be obtained from fig. 5, taking into consideration numbers of joints n_i and value of coefficient η_i. Values of coefficients η_i were calculated for the following geometrical dimensions of flange bolted connections:

- η_1: D = 0,8m; 1,2m; 1,6m; z = 10d; a_2 = 1,5d; t_p = 16mm; non-preloaded joint;
- η_2: D = 0,8m; 1,2m; 1,6m; z = 7d; a_2 = 1,5d; t_p = 16mm; non-preloaded joint;
- η_3: D = 0,8m; 1,2m; 1,6m; z = 4d; a_2 = 1,5d; t_p = 16mm; non-preloaded joint;
- η_4: D = 0,8m; 1,2m; 1,6m; z = 4d; a_2 = 3,0d; t_p = 32mm; non-preloaded joint;
- η_5: D = 0,8m; 1,2m; 1,6m; z = 4d; a_2 = 3,0d; t_p = 32mm; preloaded joint;

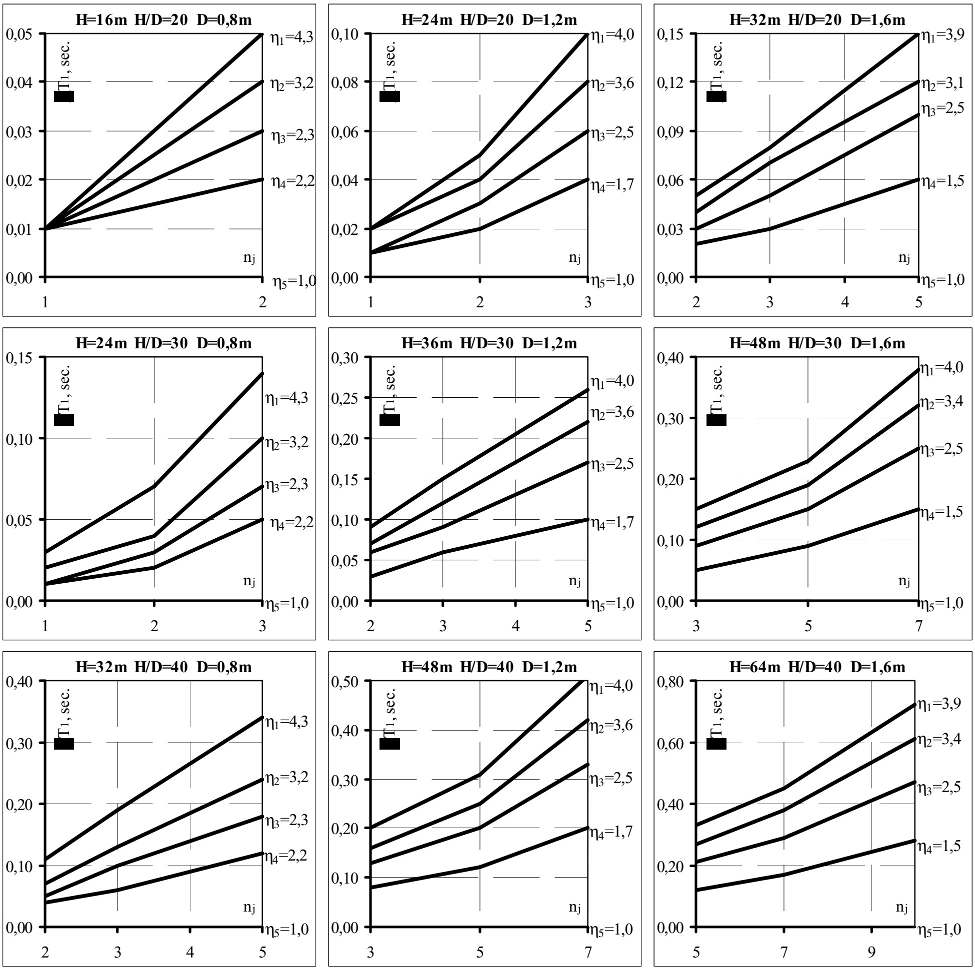


Fig. 5. Component increasing value of natural period of chimneys in relation to number of connections nj and parameter η.

6 CONCLUSIONS

On the base of the results of presented analysis the following conclusions can be drawn:

- when preloaded joints are used, the change of natural period is small and can be neglected,
- natural period of cantilevered chimneys increases with the increase of number of bolted joints and when the joint stiffness decrease,
- increase the value of natural period of self-supporting chimneys resulted from including number and stiffness of flanged bolted connections in relation to chimneys without bolted joints is up to 20% for chimneys of H/D=20, 25% for chimneys of H/D=30, and up to 30% for chimneys of H/D=40,
- simple formula (1) was modified to take into account number and stiffness of segment of chimney connections.

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