EFFECT OF STIFFENING RINGS ON BUCKLING STABILITY OF R.C. HYPERBOLIC COOLING TOWERS

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Abstract: Design and construction of efficient and economic Reinforced Concrete (R.C.) Hyperbolic Cooling Towers have driven the engineers toward the design of tall and thin-shell towers which have considerable high slenderness aspect ratio. Consequently, the shell of R.C. Cooling Towers with relative high slenderness aspect ratio is extremely prone to buckling instability due to wind loading. To increase the structural stability or buckling safety factor, one economic approach is to design and construct stiffening rings for the R.C. Hyperbolic Cooling Towers. Despite the research previously performed to determine the effect of stiffening rings on the buckling behavior of the R.C. Hyperbolic Cooling Towers, information resulting in maximum buckling stability is absent considering the optimized utilization of the quantity and dimension as well as the location of this type of stiffeners. In this paper, not only the effect of the stiffening rings on the buckling stability of the R.C. Cooling Tower is studied but also the optimized location, quantity and dimension of the stiffening rings are carried out for a sample RC Cooling Tower. The dimensions of the selected sample cooling tower are in average typical dimensions which are used in the current practice. In this study, finite element (F. E.) analyses has been carried out to define the buckling modes and resistance of this tower due to wind loading for different number of stiffening ring configurations. Based on the conducted buckling analysis, the optimized number, location and dimension of the stiffening rings that maximizes the tower's buckling stability are defined and the methodology to achieve this information is discussed in this paper.

Keywords: R.C. hyperbolic cooling towers, Concrete shell, Buckling safety factor, Finite element.

1. INTRODUCTION

Nowadays, the RC Hyperbolic Cooling Towers (or also known as the Natural Draught Cooling Towers) are constructed for a wide range of power plants. The construction of taller cooling towers requires thicker concrete shell, which results in larger dead loads. To decrease the dead loads, the concrete shell has to be designed thinner and slender, which will cause buckling instability problems in the R.C. shell due to wind and dead loads. As a result, the height to shell thickness, or slenderness aspect ratio, of the cooling towers has been significantly increased. Such slender shell structures, which are distinguished as

extreme slender reinforced concrete shell structures, usually have buckling stability problems [6 & 7].

To propose an economical and at the same time practical solution, in 1986 Form studied the stability behavior of ISAR-II R.C. Hyperbolic Cooling Towers. Based on the research he conducted, it was found that the construction of the stiffening rings increases the buckling safety factor and structural buckling stability significantly. The research conducted by Form showed that adding 2, 3, and 4 stiffening rings to the cooling tower increases the buckling safety factor of the concrete shell by a factor of 1.65, 2.32 and 2.80 respectively [3]. In 1998, the research conducted by Boseman on RC Cooling

Towers located at the Athlone Power Plant showed that the construction of stiffening rings for cooling towers increases the safety factor of the concrete shell due to buckling mode by a factor of 2.75 [2]. In both studies conducted by Form and Boseman, the details concerning different aspects of the stiffening ring such as the quantity, location and dimension of the stiffening rings, which will lead to the maximum buckling safety factor, were not covered. To achieve maximum buckling stability or safety factor, such information about the stiffening ring is essential to effectively strengthen the R.C. Cooling Towers with the help of stiffening rings.

This paper studies the effect of different aspects of the stiffening ring such as the quantity, location and dimension of the stiffening rings on the buckling stability and safety factor of the R.C. Hyperbolic Cooling Towers. It also introduces a methodology to obtain such information for any cooling towers. F.E. model of a sample R.C. Hyperbolic Cooling Tower was used to study the buckling stability which is affected by different aspects of the stiffening rings. The dimensions of the selected sample cooling tower are in average typical dimensions which are used in the current practice.

2. FINITE ELEMENT MODEL OF THE R. C. COOLING TOWERS

One of the R.C. Hyperbolic Cooling Towers of S. Montazer Qaem Power Plant located in Tehran Province is chosen for numerical modeling in this study. Fig. 1 shows the elevation view and some details of the R.C. cooling tower. The cooling tower is made of continuous cast-in-place reinforced concrete shell supported by thirty "X" shaped columns with cross-section of 700 mm by 1,050 mm. As shown in Figure 1, the selected cooling tower has a total height of 92,000 mm. The radius of the R.C. shell at the transition of columns to shell and at the throat has been measured 31,708 mm and 24,000 mm respectively. The concrete shell thickness varies throughout the height, which decreases from 1,150 mm at the columns-shell transition to 220 mm at the elevation of 31,600 mm, and from there it reduces further to 170 mm at the top. The cooling tower is built on a circular strip foundation which is 3,500 mm wide and in average 1,200 mm high and is buried 4,000 mm below grade. At the top of the cooling tower, a reinforced concrete stiffening ring (or upper stiffening ring) is designed with a thickness and width of 300 mm and 1,100 mm respectively.
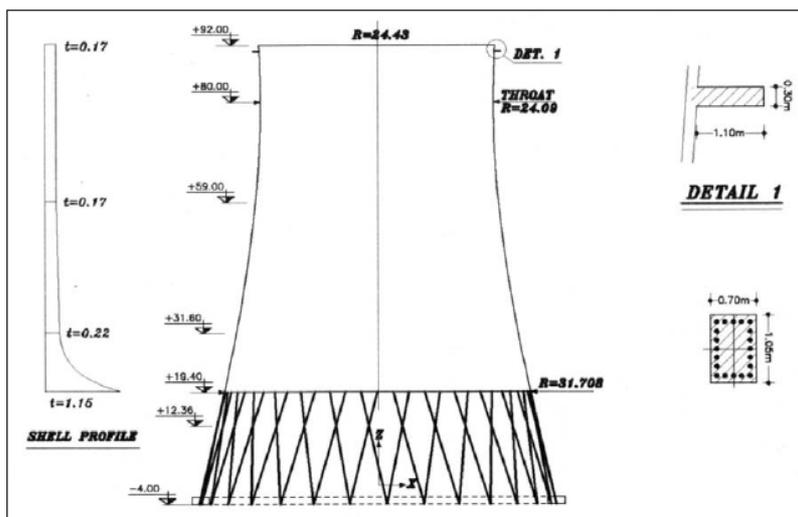

Fig. 1. Elevation and pertinent details of S. M. Qaem Power Plant's Cooling Tower.

In this study, the commercial structural analysis software, NISA-II EMRC was used for carrying out buckling analyses defining the structural stability safety factor for numerous F.E. configurations [5]. In modeling of the R.C. Hyperbolic Cooling Tower, the X-shaped columns and the strip foundation were modeled by general beam type elements. The reinforced concrete shell, the upper stiffening rings and additional stiffening rings were modeled by four-node three-dimensional R.C. shell elements with 6 degree-of-freedom at each node. The soil was simulated using general spring elements [7].

After numerous trial and errors, the number of elements was optimized for the finite element model, and the final mesh of the F.E. model is shown in Fig. 2. In this study, the cooling tower with the upper stiffening ring is referred to as the cooling tower without additional stiffening ring or simply the cooling tower and is used as benchmark for comparison with other configurations. Next, the effect of the location, thickness and width of additional number of stiffening rings will be studied on the stability behavior of the cooling tower.
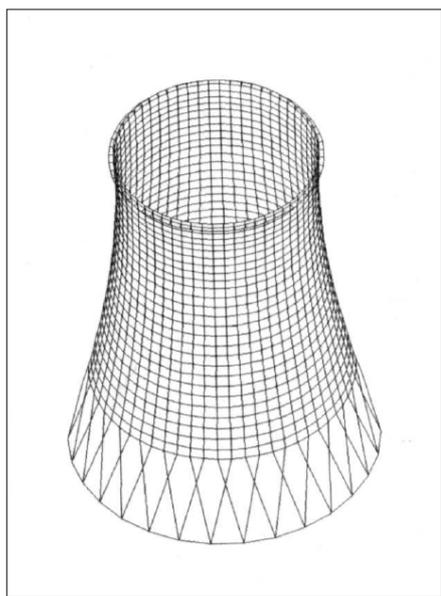

Fig. 2. Finite element mesh of the R.C. Hyperbolic Cooling Tower without additional stiffening rings.

3. OPTIMIZED LOCATION OF STIFFENING RINGS

To define the location of the stiffening rings resulting in the highest buckling safety factor, the buckling modes and minimum buckling resistance of the F.E. model was carried out for different configurations. Each configuration of the F.E. model essentially consisted of the previous arrangement of the cooling tower and an added stiffening ring of 400 mm by 1,000 mm cross-section. The added stiffening ring was located for each configuration in a different height, and in all arrangements the height of the added stiffening ring varied from 25 to 90 m. Each cooling tower arrangement was analyzed for its buckling modes, least buckling resistance and buckling stability due to code-defined wind load and its dead load. The wind load distributed in the vertical and horizontal plane of the R.C. Hyperbolic Cooling Tower were calculated based on the Iranian Code 519 (Appendix I) and the VGB Guideline Structural Design of Cooling Towers (VGB 1990) respectively [4 & 8]. Fig. 3 shows the results obtained from the buckling analysis conducted for all cooling tower configurations. As shown in Fig. 3, the configuration with the stiffening ring located at the height of 55 m from the bottom of the R.C. Hyperbolic Cooling Tower, which is approximately the mid height of the cooling tower, depicted the maximum buckling safety factor of all other stiffener arrangements in that configuration. Then again, the maximum deformation from the first buckling mode of the R.C. Hyperbolic Cooling Tower without any additional stiffening ring was found at the same height, see Fig. 4. To increase the buckling stability of the R.C. Hyperbolic Cooling Tower, an additional stiffening ring was added to the previous arrangement which consisted of the cooling tower with the first additional stiffening ring. In the second configuration, the maximum buckling safety factor was

found to be located 44m from the bottom of the tower. From the buckling analysis of the first configuration, the maximum deformation in the first buckling mode due to wind and dead loads was found in the same height.
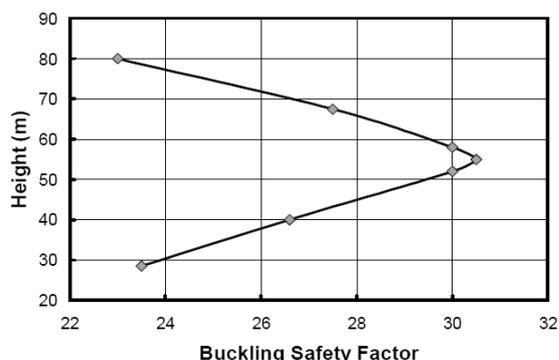

Fig. 3. Effect of stiffening ring location on the buckling safety factor of the sample cooling tower.

Throughout the next configurations, it has been found that an analogous methodology can be applied in adding extra stiffening rings to the tower. The method is such that first of all the location of the maximum deformation of the first buckling mode for the R.C. Hyperbolic Cooling Tower with all its previously added stiffening rings is obtained due to wind and dead loads. Then the subsequent stiffener is placed at this location to obtain the maximum buckling safety factor.

It is worthwhile to mention that for the sample F.E. model, adding a third or more stiffeners to the R.C. Hyperbolic Cooling Tower causes the maximum buckling deformation of the first buckling mode to transfer from the concrete shell to the columns. The buckling deformation's shift to the X-shaped columns is not desired in design of this type of structures since alternative uneconomic stiffening method is then required to create sufficient buckling safety factor for the columns. Next the optimized quantities and dimensions of the stiffening rings are studied.
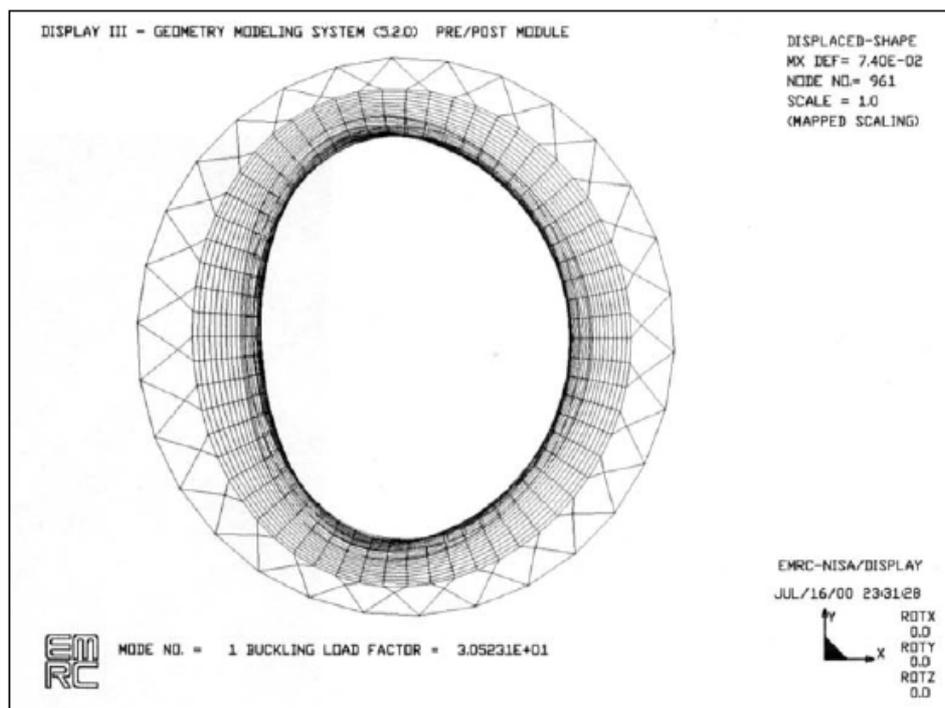

Fig. 4. Plan view of the sample RC cooling tower with maximum deformation of the first buckling mode due to dead and wind loads.

4. STIFFENING RING'S THICKNESS AND QUANTITY EFFECT ON BUCKLING STABILITY OF R.C. HYPERBOLIC COOLING TOWERS

To study the effect of the stiffening ring's thickness on the buckling safety factor of the R.C. Hyperbolic Cooling Towers, it was decided to use the above-mentioned configurations with stiffening ring arrangements resulting in the maximum buckling safety factor. Thus the first configuration, which had one stiffening ring placed in the height of 55 m from the bottom of the tower, was selected with the only difference that the stiffener thickness was no longer a constant parameter and it was considered to vary from 100 mm to 1,000 mm. On the other hand, the width of the stiffening ring was selected a constant value of six times the minimum concrete shell width, which is 1,020 mm. Buckling analyses due to the wind and dead load were conducted for this configuration to obtain the buckling mode, the least buckling resistance load and the buckling safety factor. The buckling safety factor of the first configuration obtained for each thickness of the stiffening rings is shown in Fig. 5. As shown in Fig. 5, the increase of the stiffening ring's thickness results in increase of the buckling safety factor. For thin stiffening rings, the safety factor grows significantly whereas its increase-rate becomes zero once the stiffener's thickness approaches larger values, i.e. 400 mm, see Fig. 5.

Consequently, the effect of the thickness of two stiffening rings on the buckling safety factor was investigated by adding a second stiffening ring to the R.C. Hyperbolic Cooling Towers with the first stiffening ring. The second ring was placed at the height of 44 m from the bottom of the tower. As mentioned previously, this height was defined from the maximum deformation of the first buckling mode of the R.C.

Hyperbolic Cooling Towers with the first added stiffening ring. The dimension of the second stiffener was defined as same as that of the first stiffener. That means the width of the second stiffener was also selected a constant value equal of six times the minimum shell thickness, and the thickness of both stiffener were identical and varied simultaneously from 100mm to 1,000mm. Fig. 6 shows the outcomes of the buckling analysis due to wind load for the R.C. Hyperbolic Cooling Towers with two stiffening rings. As shown in Fig. 6, the thickness of both stiffening rings was selected in the range from 100 to 1,000 mm and the cooling tower without additional stiffeners was also considered for comparison purposes.
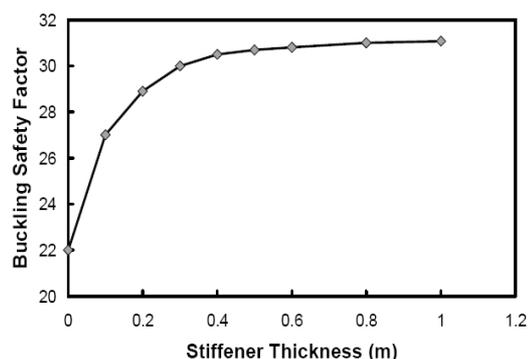
Fig. 5. Stiffening ring's thickness versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with one stiffening ring under dead and wind load.
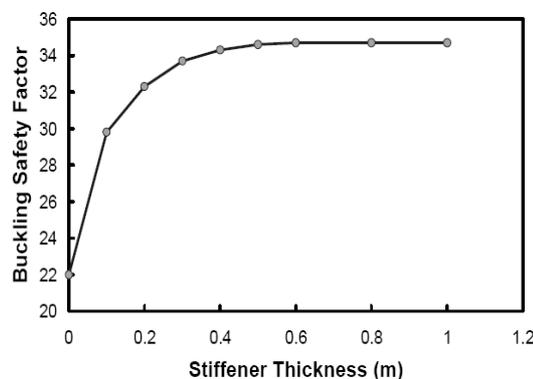
Fig. 6. Stiffening ring's thickness versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with two stiffening rings under dead and wind load.
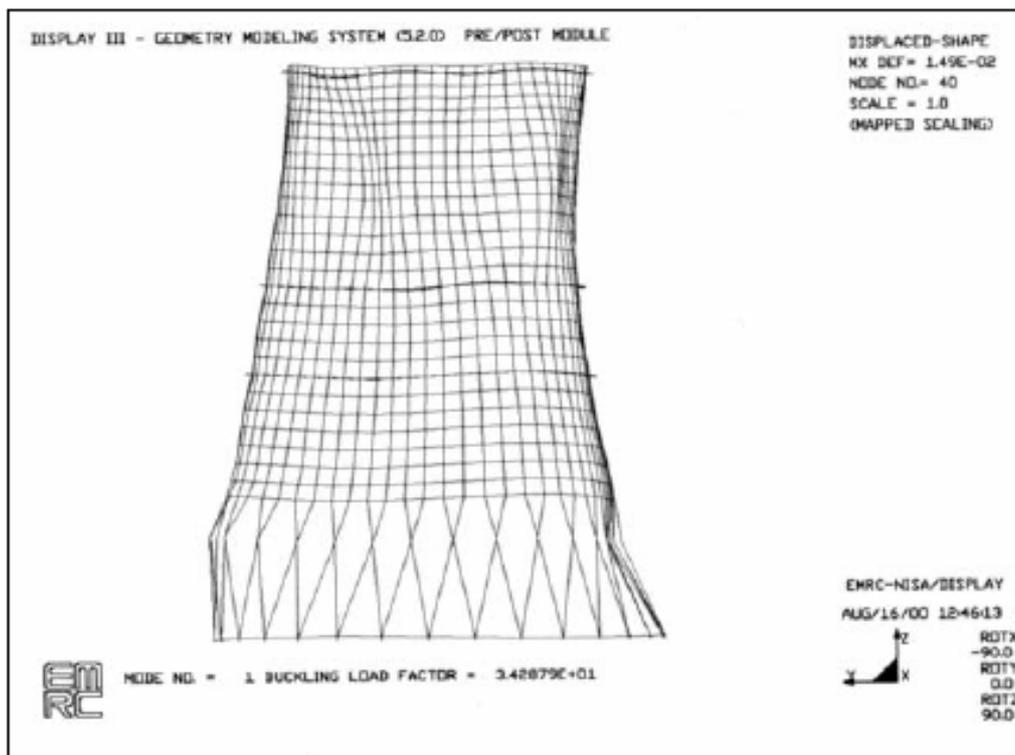
Fig. 7. Deformed shape of the first buckling mode due to wind and dead loads for the R.C. Hyperbolic Cooling Tower with two stiffening rings at 44m and 55mm height.

Similar results to those of the R.C. Hyperbolic Cooling Tower with one added stiffening ring shown in Fig. 5 were obtained for the cooling tower with two added stiffeners. Also for this case, it was noted that the increase of the stiffener's thickness causes the buckling safety factor of the cooling tower with two added stiffeners to increase. The increase rate of the buckling safety factor reduces significantly once the stiffener's thickness reaches larger values, e.g. 400 mm. At this value, the slope is adequately close to zero to be assumed that no significant increase in buckling safety factor will happen due to further increase in stiffeners' thickness.

It is worthwhile to mention that for stiffener thickness of 300 mm or larger, the deformation of the first buckling mode of the cooling tower with two additional stiffening rings commenced to shift from the concrete shell to the X-shaped columns. Fig. 7 shows the first buckling mode of the R.C.

Hyperbolic Cooling Tower with two stiffening rings that have a thickness larger than 300 mm. As shown in Fig. 7, the X-shaped columns underwent a significant amount of buckling deformation in the first mode of buckling, which is not desired in the design of such structures. To maximize the buckling safety factor, the number of the stiffeners has to be optimized and since stiffeners with thickness of 300 mm and larger causes buckling deformations in the columns, a third stiffening ring is not recommended to be added to the tower. On the other hand, to achieve higher buckling safety factor for towers with stiffening rings' thickness smaller than 300 mm, a third or fourth stiffening ring is suggested. Higher numbers of stiffeners are only suggested under the circumstance that the buckling deformation is still occurring in the concrete shell of the tower and not in the columns. To determine the location of the third and fourth stiffening ring, it was assumed that all

stiffeners have a thickness less than 300mm. The maximum buckling safety factor was obtained once the new stiffener was located at the location of the maximum deformation due to first buckling mode of the model with the previous stiffening rings. Fig. 8 shows all results obtained from the buckling analysis performed for the R.C. Hyperbolic Cooling Towers with one, two, three or four additional stiffeners with various thicknesses. As shown in the same figure, increase of the number and thickness of the stiffening rings causes the buckling stability or safety factor to rise, but the increase rate of the buckling safety factor reduces significantly once the thickness value approaches 400 mm. The buckling safety factor is insensitive to the increase of the stiffening rings' thickness beyond 400mm.
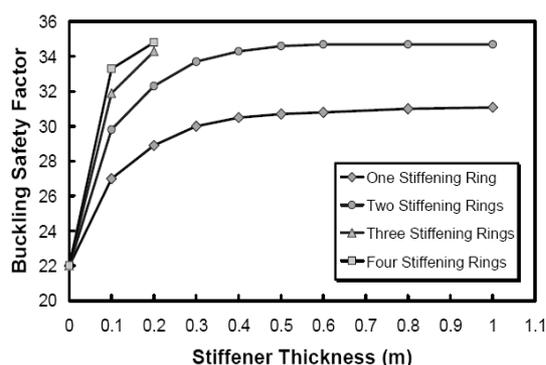

Fig. 8. Stiffening ring's thickness versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with different numbers of stiffening rings.
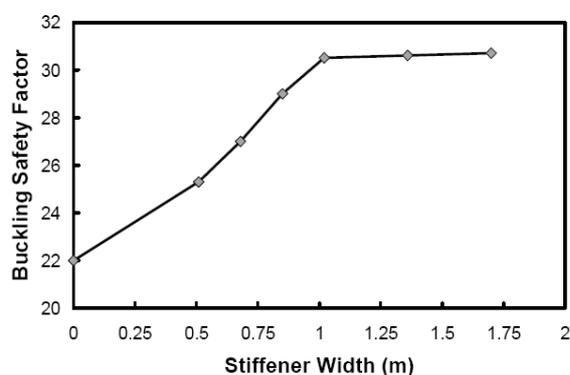

Fig. 9. Stiffening ring's width versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with one stiffening ring.

Further more, the addition of a third or fourth stiffening ring with a thickness of 300 mm or less does not increase the safety factor as much as that of two stiffening rings with a thickness of 400 mm does. To increase the structural buckling stability, it is suggested that the thickness of the first and second added stiffening ring is increased instead of adding extra stiffeners to the R.C. Hyperbolic Cooling Towers. This is because the construction process of the stiffening rings is complicated and expensive and also it is uneconomical to construct stiffening rings with thickness of 200 mm or less.

Additionally, from Fig. 8 the relationship of the stiffener's thickness versus the buckling safety factor was found to be of higher order. This is because the thickness of the stiffening ring is a function of the stiffening ring's moment of inertia. In the moment of inertia formulation, which defines the stiffness of the stiffening rings, the thickness is of 3rd order.

5. STIFFENING RING'S WIDTH AND QUANTITY EFFECT ON BUCKLING STABILITY OF R.C. HYPERBOLIC COOLING TOWERS

The width effect of the stiffening rings on the buckling stability and buckling safety factor is investigated by using the configurations of the cooling tower with stiffening ring arrangements resulting in the maximum buckling safety factor. The stiffening ring thickness was considered a constant value of 400 mm, and the stiffening ring width was assumed to be a variable in the first configuration, varying from three to ten times the minimum shell thickness which is 510 to 1,700 mm respectively. Figure 9 shows the results of the buckling analysis for the tower with one stiffening ring. As shown in Fig. 9, the increase of the stiffener's width causes the buckling safety factor to rise, but similar to the characteristics obtained for the buckling safety factor versus the stiffening

ring's thickness shown in Figs. 7 and 8, the growth rate of the buckling safety factor decrease significantly once the stiffener's width value approaches six times the minimum shell thickness or larger. This means that the buckling safety factor is unaffected by stiffener's width values larger than six time the minimum shell thickness.

Moreover, a second stiffening ring was added to the cooling tower at the optimized height of 44 m as previously defined in this study. In this configuration, the dimension of the second stiffener was defined as same as that of the first stiffener. That means the thickness of the second stiffener was also selected a constant value equal to 400 mm and the width of both stiffener were identical and varied simultaneously from 510 mm to 1,700 mm. The width of both stiffeners was simultaneously increased similar to the last configuration and consequently the buckling safety factor of the model was obtained from buckling analysis conducted for each increase of the stiffeners' width. The results of these analyses are shown in Fig. 10. As shown in Figure 10, the buckling safety factor versus stiffener's width relationship of the cooling tower with two stiffening rings is similar to that with one stiffener shown in Figure 9. The increases rate of the buckling safety factor is steep for stiffeners with narrow width but then the rate slows down significantly once the width approaches six times the minimum shell thickness. The buckling safety factor is insensitive to any increase in the shell width for values of six times the minimum shell thickness or larger. From the analysis conducted for the R.C. Hyperbolic Cooling Tower with two stiffeners, it was found that the stiffener width of six times the minimum shell thickness or larger causes the buckling deformation of the first buckling mode to transfer from the concrete shell to the X-shaped columns. Also it was found that the addition of more stiffeners is not effective on the increase of the buckling safety factor.

Therefore the addition of more stiffeners is not recommended for the sample cooling tower with two stiffeners that have a width equal to six times the minimum shell thickness or wider. On the other hand, if the width of the two stiffeners are less then six times the minimum shell thickness, more stiffener causes the buckling stability of the tower to increase and therefore it is recommended to add more stiffener unless buckling deformations commences to appear in the columns. The results of buckling analysis conducted for the R.C. Hyperbolic Cooling Tower with three stiffeners are shown in Fig. 11, which is in good agreement with the results obtained for the towers with one and two stiffeners shown in Figs. 9 and 10.
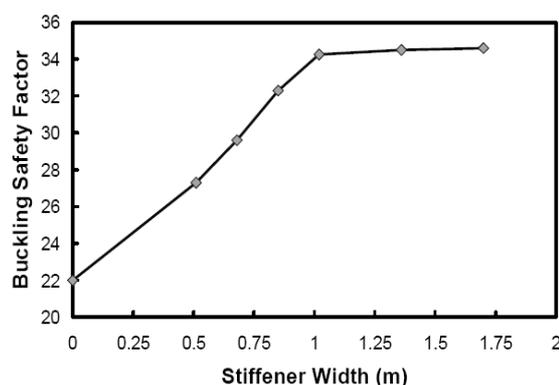

Fig. 10. Stiffening ring's width versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with two stiffening rings.
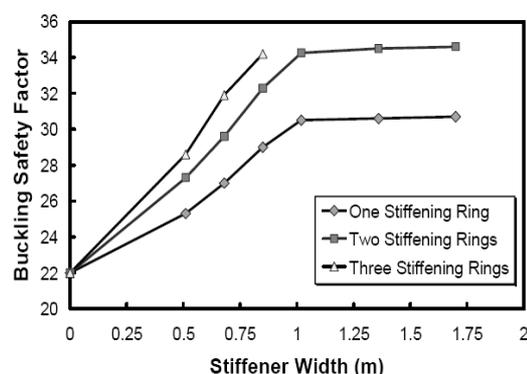

Fig. 11 Stiffening ring's width versus buckling safety factor for the R.C. Hyperbolic Cooling Tower with various numbers of stiffening rings.

Fig. 11 shows all results obtained from the buckling analysis performed for the R.C. Hyperbolic Cooling Towers with one, two or three stiffeners with various widths. From this figure it is found that the buckling safety factor of the cooling tower with three stiffeners which have stiffening ring's width of five times the minimum shell thickness is approximately equal to that of the tower with two stiffeners which have stiffener's width of six times the minimum shell thickness. Given the complicated and expensive construction process of stiffening rings for the R.C. Hyperbolic Cooling Towers, it is highly suggested that no more than two stiffeners with sufficient width should be designed to increase the buckling safety factor.

Also, it was found that the relationship of the stiffener's width versus the buckling safety factor is more and less linear. The stiffening ring's moment of inertia is a function of the width of the stiffening ring. In the moment of inertia, which defines the stiffness of the stiffening rings, the width is of first order.

6. DISCUSSION AND CONCLUSION

The sample R.C. Hyperbolic Cooling Tower located at S. M. Qaem Power Plant has dimensions which are good representation of the average dimension of this type of structures. The study on this sample cooling tower provided constructive insight into the behavior of similar type of cooling towers. Based on the above-mentioned investigation conducted, the findings for the quantity, the location and dimension of the stiffening rings and their effect on the buckling safety factor of the sample cooling tower are summarized in the following:

1. The location of the maximum deformation due to the first buckling mode of the R.C. Hyperbolic Cooling Tower without any stiffener is found to be identical to the location of the first stiffening ring which results in the highest buckling safety factor. Similarly, the optimized location of the second stiffening ring is the same as the location of the maximum deformation of the first buckling mode of the R.C. Hyperbolic Cooling Tower with the first stiffener. Based on the same method, if more stiffeners are required, the next stiffening ring is placed at the maximum buckling mode deformation of the tower with all previous added stiffening rings.

2. To obtain the maximum buckling safety factor of the concrete shell, the optimized thickness of the stiffening rings is found to be a function of the buckling behavior, buckling resistance and buckling mode shapes of the R.C. Hyperbolic Cooling Tower. For the sample cooling tower, the optimized thickness of the stiffening rings was carried out to be 400 mm whereas higher thicknesses did not increase the buckling safety factor.

3. Also, the optimized width of the stiffening rings, which provides the maximum buckling safety factor of the concrete shell, is found to be also a function of the buckling behavior and characteristics such as buckling mode shape and resistance of the R.C. Hyperbolic Cooling Tower. The optimized width of the model was carried out to be six times the minimum shell thickness and higher widths did not increase the buckling safety factor.

4. Based on the studies performed on the sample tower, if the width and thickness of the stiffener rings are selected as mentioned in the statements number 2 and 3, higher numbers of the stiffener rings will not considerably affect the structural buckling stability of the sampling cooling tower. Higher amount of stiffeners for the cooling tower with optimized stiffener's dimension could cause buckling deformation in the columns, which is not desired. Therefore because of the economics and the

construction complexity of the stiffener rings, it is suggested that instead of designing more then two stiffener rings the dimension of these stiffeners are selected efficiently.

Based on the above finding it is concluded that the added stiffening ring increases the buckling resistance of the concrete shell. Dependent to the dimensions of the stiffening rings the ring will behave flexible or rigid. For flexible stiffening rings, which have smaller dimensions, it was observed that larger numbers of stiffeners are required to maximize buckling safety factor as efficient as a rigid stiffener does, which has larger dimensions. Also, it was observed that the buckling deformation was extended to the columns due to over strengthening the concrete shell by stiffening rings. This phenomenon has to be not only considered but also avoided in the design of stiffening rings for the R.C. Hyperbolic Cooling Towers. Additionally, it was found that the relationship of the stiffener's width versus the buckling safety factor is more and less linear whereas that of the stiffener's thickness versus the buckling safety factor is of higher order. To explain it, the thickness and width of the stiffening ring have been related to the stiffening ring's moment of inertia. In the moment of inertia, which defines the stiffness of the stiffening rings, the thickness is of 3rd order whereas the width is of first order. In this paper a simple optimization methodology was adapted to define the effect of the quantity, thickness and width of the stiffening rings on the maximum buckling safety ratio for a sample cooling tower with different stiffening configuration. As a result, a methodology were proposed for defining the optimized stiffening ring's parameters such as the quantity, dimensions and location to obtain the maximum buckling safety ratio for the sample cooling tower. This method can be utilized as a benchmark for design practice and can be applied for similar cooling towers.

APPENDIX I

The pressure distribution proposed by "Minimum design load for ordinary buildings and structures, Standard # 519" is shown in Equation (1). The pressure is distributed as a function of height. In Equation (1), P stands for the pressure with the unit of Pa and H is the height of the structure in meters [4].

$$p = \begin{cases} 735p_a & \text{for} & H \le 10m \\ 980p_a & \text{for} & 10m < H \le 20m \\ 1325p_a & \text{for} & 20m < H \le 100m \\ 1325p_a + 125p_a \,(\text{for each } 30m) & \text{for} & H > 100m \end{cases}$$

Eq. (1)

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