https://doi.org/10.3311/PPci.20731

Periodica Polytechnica Civil Engineering, 67(2), pp. 473–484, 2023

Analysis of the Shear Stress State at the Native Material/Repair Material Interface in Cooling Towers

Ryszard Kutyłowski[1*]

[1] Faculty of Civil Engineering, Wrocław University of Science and Technology, Wybrzeże St. Wyspiańskiego 27, 50-370 Wrocław, Poland
[*] Corresponding author, e-mail: ryszard.kutylowski@pwr.edu.pl

Received: 26 June 2022, Accepted: 15 January 2023, Published online: 02 February 2023

Abstract

The structure of the cooling tower shell locally made of materials differing in their specifications is considered. Such structures are created as a result of cooling tower shell repairs or reinforcements. The results of an analysis of the distribution and magnitude of shear stress at the interface between layers made of different materials are presented.

Keywords

cooling tower shell, strengthening, repair assessment, shear stresses, delamination failure

1 Introduction

This paper deals with one of the problems arising in a structure renovated with materials whose specifications differ from those of its native material. The problem is considered for the cooling tower shell renovated by replacing its native material with a new material strengthened with ribs or large-area reinforcements.

One should note that the use of materials differing in their specifications is the cause of debonding (delamination) and the absence of interaction between the newly incorporated material and the native material of the cooling tower.

The frequently reported cases of the debonding of the repair material from the cooling tower shell material provided a stimulus for undertaking research on this subject. The problem is especially evident in the case of repairs covering relatively large areas of the shell and also when the strengthening consists in spraying shotcrete onto the native material. It should be noted that after such repairs it is in these areas that cracks and repair material delaminations reoccur after some time (Fig. 1). Once the repair material debonds, it undergoes accelerated degradation manifesting itself in its cracking and spalling. Fig. 2(a) shows an example of a spalled shotcrete material debonded from a cooling tower. By removing some of the shotcrete the degree of its debonding from the native material was revealed (Fig. 2(b)). In Fig. 2(c) one can see the area from which the shotcrete has fallen off and that the remaining shotcrete is debonded. For the structure to be really strengthened the two materials should work together. The direct cause of debonding in such cases is the difference in the E-modulus between the native material and the repair material.

After years of being in service cooling towers are periodically renovated. It often happens that during the successive renovations materials differing in their specifications are superimposed on one another. In such a case, i.e., when the cooling tower shell is no longer homogeneous, this fact should be taken into account in the calculations.

Moreover, the results of an analysis of the distribution and magnitude of the shear stresses occurring at the native material/repair material interface after the renovation or reinforcement of the cooling tower are reported. This analysis complements the analysis of the stress state of the cooling tower shell under all the relevant loads and it should always be carried out as part of cooling tower load-bearing capacity check calculations performed after an extensive cooling tower renovation.

Fig. 1 Cracked surface of repair material

Cite this article as: Kutyłowski, R. "Analysis of the Shear Stress State at the Native Material/Repair Material Interface in Cooling Towers", Periodica Polytechnica Civil Engineering, 67(2), pp. 473–484, 2023. https://doi.org/10.3311/PPci.20731

Fig. 2 Examples of repair material (shotcrete) debonding from native material of cooling tower

The distribution and values of shear stress in the cooling tower shell change from the design ones when the cooling tower renovation consists in replacing the degraded concrete with other concrete whose E-modulus value differs from that of the cooling tower's native material. Shear stress in the cooling tower shell also increases when the native concrete is strengthened with reinforced ribs or a new continuous reinforced coat or when the cooling tower shell is sprayed with unreinforced shotcrete. In each of the cases the shotcrete layer adds to the cooling tower shell thickness. Shotcrete debonding cases were reported in, i.a., Martin [1].

The analysis presented in this section deals with the stress state of a superficially continuous connection between two materials.

In most cases, materials with higher specifications than the ones characterizing the native material are used for renovation. Then the approach presented in this paper is applicable. Cases when materials with similar or almost identical specifications are used for renovation are rare [2].

In descriptions of repair designs it is usually proposed to use materials conforming to the ones from which the structure was built (e.g., the chimney in [3]) or repair materials satisfying the correspondence criteria [4]. But some of the recommendations which the owner of a cooling tower receives after a structural survey of the latter do not contain detailed repair material specifications. In such cases the contractors use materials characterized by much higher parameters than the native material, which results in the quick degradation of the repaired areas. This manifests itself in cracking and delamination and consequently, in the spalling of the repair material. The contractors often do not demand any data on the material properties from the material producers and the spec sheets quite commonly lack information about the Young's modulus of the repair material and they often do not provide any information about the material compatibility, focusing only on the strength and completely neglecting the values of the Young's modulus of the native material and the repair material [5]. Many aspects of degradation which cooling towers are subject to after many years of being in service were extensively discussed in [6]. The paper described the process of identifying the actual performance of a cooling tower, taking into account all the loads, the defects in workmanship and other aspects of the cooling tower behaviour, among others delamination and stiffness degradation. What is very important, it was indicated in [6], that the homogenous model of cooling tower material should be changed. As an example, in this paper the increasing of shear stresses at the interface between native and repair materials is presented. Unfortunately, until these days only homogenous models of new cooling towers are presented in the literature. For example, in [7] and [8] an analysis of the elements used for a new cooling tower is done. The homogenous model of the cooling tower still persists in 2020 (see [9]).

Review publications such as [10], which contains an extensive literature survey highlighting many aspects of the issues relating to the interaction between concretes of different age, are highly relevant to the subject of this paper. Study [10] discusses the methods used to test the strength of the bond between concretes of different age and indicates factors having a bearing on the durability of this bond. Appropriate experimental investigations were carried out, showing that the durability of the bond to a large degree depends on the mechanical and physical properties of the bonded materials, which corroborates the validity of the research reported in the present paper.

The publications cited in the present paper are in English. The exception is study [11] which indicates significant increases in stress in precast concrete units in cases when the "old" concrete of the prefabricated units was covered with repair concrete.

In study [12] it was shown that the direct bonding of "old" concrete and "new" concrete, even when they are the same concretes or concretes of very similar strength class, leads to debonding as the failure mechanism. This corroborates the observations made in the present paper, especially in Fig. 2 where the debonding of the two concretes is clearly visible. The conclusions reported in [12] were drawn on the basis of laboratory splitting tests carried out on concrete specimens in which 14 days after they had been made half of the specimen concrete had been replaced with new concrete. The specimens were subjected to compression and they would fail due to debonding in the contact plane. Besides debonding, slight damage to the "new" concrete was observed. The concretes were of the same strength class or they differed by one class.

The validity of the research reported in the present paper is confirmed in study [13], where on the basis of experimental investigations it is noted that the difference between the E-moduli has a bearing on the stresses in the bond between two materials. The considered difference in Young's modulus values amounted there to maximum 10%. Whereas in the present paper this problem was considered up to a difference as large as 70%. It should be noted that the consideration of so large differences between the E-moduli is very much justified as it is based on actual observations – so large differences between the E-moduli have been noted in practical repairs of reinforced concrete structures, especially large-area repairs of cooling towers. A broad analysis of problems relating to the preparation of a concrete structure repair design was carried out in study [14]. It was noted that among the parameters having a bearing on the susceptibility of cement materials to cracking the Young's modulus of the repair material is of major consequence, and that the higher this modulus in comparison with the native material, the greater the stresses causing the degradation of the structure's material. In study [15] it was also found that the durability of the bond depends on the mutual proportion of the E-moduli of the materials being bonded.

In [14] it was noted that differences in the rigidity of two concretes bonded together were not taken into account in the literature, despite the fact that sometimes materials differing in their Young's modulus values are bonded together. Experimental investigations aimed at evaluating the durability of such a bond were presented in paper [16]. It was shown that the difference in rigidity between the bonded materials significantly affects the durability of the bond. It was also suggested that the relevant standards should cover the use of repair materials whose parameters differ from those of the native material. Sadowski et al. [17] referred to relevant standards, i.e., to Eurocode 2-1-1 and FIB Model Code 2010 recommendations concerning shear stress in the bond between two concretes, and on the basis of experimental investigations it was found that the recommendations did not fully reflect the actual behavior of the bond. Also, in Kang et al. [18] reference was made to Eurocode and experimental investigations were carried out to verify the Eurocode's formulas for calculating the shear strength at the interface between two concrete layers having identical or different compressive strength. Compression tests of two concrete layers were carried out in the direction parallel to the bond between the layers. The concrete layers were joined together with rebars. It was found that especially in the case of higher class concretes the experimentally determined compressive strength was higher than the one calculated from the Eurocode formula. It should be added that the Eurocode formulas are general formulas for a connection design. In the present paper it is shown that the stress in the bond further increases when materials characterized by different parameters are bonded together.

Similar research is presented in Wang et al. [19] where the effectiveness of bonding between new high-strength concrete and old concrete was tested. The tests were carried out for many degrees of roughness and different bonding agents for the period of 28 days, 120 days and 1 year. On the basis of the test results the effect of different factors on the durability of the bond between the "old" concrete and the "new" concrete was identified. Relevant laboratory investigations are conducted in many research centers worldwide. For example as part of study [20] laboratory pure shear tests were carried on a specimen consisting of "old" and "new" concrete differing by one class. The effect of different bonding parameters was studied.

Research on the effectiveness of bonding concrete to concrete features prominently in the literature on the subject. In this regard a major consideration is the need to ensure a proper moisture content of the substrate prior to placing repair concrete layers [21] as this affects the durability of the bond. The effect of native concrete surface treatment aimed at ensuring proper adhesion to the repair concrete, with and without the use of a bonding coating, was studied in [22]. Further research on the durability of such bonds is reported in [23].

Experimental studies of the bond between "old" and new concrete predominate in the literature. The "old" concrete is concrete prepared a few weeks or maximally a year before testing. One should bear in mind that specimens made and tested in a laboratory do not always work in the same conditions as concrete built into a structure, especially into a large-area structure such as a cooling tower.

To sum up, it emerges from this literature review that very seldom attention is paid to the fact that materials debond because they differ in their mechanical and physical parameters. It is hard to find studies which would show how a disparity between the E-moduli contributes to an increase in shear stress in the bond, which is the direct cause of debonding. Therefore, the present author addressed this problem and has shown that the increases in shear stress are significantly large, indicating that this is the direct cause of debonding as materials with different E-moduli deform differently whereby additional shear stresses arise. The analysis presented in this paper was carried out from the point of view of structural mechanics and it draws attention to this previously disregarded significant problem.

2 General remarks on analysis of shear stress state at native material/repair material interface

Next sections present the results of an analysis of the distribution and magnitude of shear stress between the layers of the native material and the repair material after the renovation or strengthening of the cooling tower shell. Let us repeat, this analysis is supplementary to the analysis of the stress state resulting from subjecting the cooling tower shell to all the standard loads.

In the extreme case, an increase in shear stress can lead to the debonding of the two materials and cause a reduction in the interaction between them. This means that the repair consisting in replacing a material or adding ribs or superficially spraying with shotcrete did not serve its purpose from both the technical and economic point of view.

In order to provide specific calculation results, analyses were carried out for existing 132 m, 100 m and 66.5 m high cooling towers. The comparative calculations, making it possible to evaluate shear stresses at the interface between the cooling tower shell's native material and the repair material were performed for the cross section of a shell with thickness *h* and unit circumferential width *b*.

Also the relative increases in stress are given to make the analysis most general and universal and to illustrate the problem of the increase in stress at the interface between the materials used. The aim was to show the consequences of a repair made using improper materials.

The relative increases in shear stress are only and exclusively due to the use for repair or strengthening purposes of a material with different parameters (in this case the E-modulus) than those of the native material. The increases in shear stress cause a cohesive and adhesivc failure. The considerations are not case specific. For an exemplary cooling tower under a given load it was shown how after the use of improper repair material shear stresses increase, resulting in a cohesive and adhesivc failure of the repair material.

3 Shear stress analysis for concrete replacement (repair)

The calculations were carried for two concrete replacement depths: 1) h_1 = 3 cm and 2) h_1 = 6 cm (Fig. 3). The above replaced concrete thickness values exhaust all the known practical cases – concrete losses usually do not exceed the thickness of 3 cm and in cases of greater damage, they do not exceed the thickness of 6 cm. The cooling tower shell thickness was assumed to remain the same as before the repair and to agree with the design thickness. The cooling tower shell's cross section modified as described below was considered in the calculations.

It is assumed that, as it is actually observed in practice, the repair materials used are characterized by a higher E-modulus than that of the native material of the cooling tower shell. The higher E-modulus value in the cross section's part with thickness h_1 was taken into account by commensurately increasing the width of the cross section (by the value $(p - 1) \cdot b$), where $p = \frac{E_1}{E}$, E is the E-modulus of the native material and E_1 is the E-modulus of the repair material). In the cross section created in this way, stresses across the shell thickness marked with line 1–1 in Fig. 3 were determined. The stresses occurring in this cross section were denoted as τ_1. They were compared with the stresses (denoted as τ) determined across the same thickness 1–1 in a cross section with width *b*, made of the cooling tower shell's native material. Axis *y* is always the central axis of the cross section – both the one made of the native material and the modified one. This means that in the cross section incorporating the repair material this axis will always be situated below *h*/2 from axis y_1. The calculations were performed for different values of *p*: *p* = 1.1, *p* = 1.3, *p* = 1.5, and *p* = 1.7. This range of *p* (the latter being a ratio of the E-modulus of the repair material to that of the native material) exhausts the practical cases of materials used for repairs and renovations.

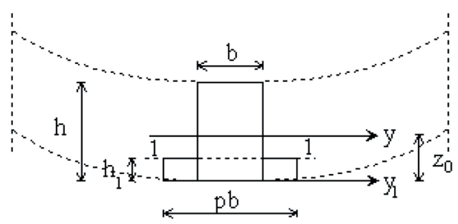

Fig. 3 Repaired cooling tower shell model for determining shear stresses at interface between two materials

It should be noted that shear stress in the cross section for a given lateral internal force depends on the moment of inertia, the static moment of the "cut off" part of the cross section and the width of the latter.

$$\tau_{xz}(z) = \frac{T_z(x)\overline{S_y}(z)}{I_y b(z)} \tag{1}$$

Figs. 3 and 4 show how to take into account the different Young's modulus of the repair material by appropriately increasing width b, depending on the E_1/E ratio (coefficient p). The modified cross section shown in the figures is an equivalent cross section. Stresses τ_1 and τ are calculated from Eq. (1). All the quantities in the formulas for τ and τ_1 are calculated using respectively the standard cross section and the equivalent cross section. In the expression for τ the moment of inertia and the static moment of the cross section's "cut off" part are calculated for the main centroidal axes of the cross section, taking into account the latter's height h and width b. In the expression for τ_1 the moment of inertia and the static moment of the cross section's cut off part are calculated for the main centroidal axes of this modified cross section, taking into account the latter's height h and modified width b depending on ratio E_1/E.

The results of the calculations are collated in Tables 1–6. The first column in the tables shows the values of the characteristic cooling tower heights, counting from level +0, at which shell thickness changes. The first row in each of the tables shows the level from which the cooling tower shell begins.

The cooling tower supports are 8 m, 5 m and 3.5 m high in respectively 132 m, 100 m and 66.5 m high towers. The second column in the tables shows shell thickness values corresponding to the cooling tower heights. Then τ_1/τ shear stress ratios for different values of parameter $p = E_1/E$ are given for the particular cooling tower heights.

Table 1 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 3 cm and 132 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
8	66	1.082	1.237	1.383	1.519
15	42	1.072	1.207	1.329	1.441
22	18	1.046	1.125	1.191	1.247
68	14	1.036	1.096	1.144	1.184
128	14	1.036	1.096	1.144	1.184
129	20	1.050	1.137	1.210	1.273
132	26	1.059	1.165	1.256	1.337

Table 2 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 3 cm and 100 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
5	40	1.071	1.203	1.323	1.431
30	12	1.029	1.077	1.115	1.146
100	12	1.029	1.077	1.115	1.146

Table 3 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 3 cm and 66.5 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
3.5	30	1.063	1.183	1.280	1.370
11.5	15.2	1.039	1.105	1.160	1.205
13.5	13.2	1.033	1.089	1.133	1.170
15.5	12	1.029	1.077	1.115	1.146
66.5	12	1.029	1.077	1.115	1.146

Table 4 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 6 cm and 132 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
8	66	1.066	1.187	1.295	1.391
15	42	1.052	1.142	1.219	1.285
22	18	1.017	1.044	1.063	1.078
68	14	1.006	1.015	1.019	1.021
128	14	1.006	1.015	1.019	1.021
129	20	1.021	1.056	1.082	1.103
132	26	1.033	1.087	1.130	1.166

Table 5 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 6 cm and 100 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
5	40	1.050	1.137	1.210	1.273
30	12	1.000	1.000	0.990	0.982
100	12	1.000	1.000	0.990	0.982

One can see that the values of τ_1 relative to τ significantly increase as parameter p increases. The number of rows in the tables depends on the available information on the cooling tower shell thickness at the particular heights. Especially in the case of 100 m high cooling towers there were few available data. Nevertheless, the most essential tendencies are visible also in this case.

Table 6 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 6 cm and 66.5 m high cooling tower, ($p = E_1/E$)

H [m]	h [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
3.5	30	1.039	1.104	1.157	1.201
11.5	15.2	1.010	1.024	1.034	1.040
13.5	13.2	1.004	1.008	1.008	1.007
15.5	12	1.000	1.000	0.990	0.982
66.5	12	1.000	1.000	0.990	0.982

Shear stress reaches higher values in areas where the shell is thicker and it is the highest starting from the level from which shell thickness amounts to 14 cm in the case of 132 m high cooling towers and to 12 cm in the other cases. The higher the cooling tower, the higher the stress value.

Slightly smaller stress increases occur in the (132 m high) cooling tower crown zone. The calculation results were obtained taking into account the stiffness of the cooling tower shell alone. The upper ring in the cooling tower crown zone considerably stiffens the cooling tower structure (hence the increase in shear stress in this zone is clearly smaller than the calculated one), but this stiffness was neglected in the calculations.

The stress values are higher for replacement to the depth of 3 cm than to the depth of 6 cm. The maximum increase in shear stress amounted to 51.9% at $h_1 = 3$ cm and to 39.1% at $h_1 = 6$ cm. The increase in shear stress at the interface of the materials grows with the value of coefficient $p = E_1/E$.

4 Shear stress analysis for cooling tower strengthening with additional coat

This cooling tower shell analysis concerns two types of cooling tower shell strengthening under the full bond assumption. First, cooling tower strengthening with a 6 cm thick layer of sprayed steel fibre-reinforced shotcrete was analysed. Six centimetres is considered to be the minimal practicable thickness for cooling tower strengthening with SFR shotcrete ensuring the minimum thickness of the reinforcement cover. Then a case of spraying an unreinforced shotcrete layer with thickness $h_2 = 3$ cm was considered. This kind of repair is used when the existing shell reinforcement cover is found to be insufficiently thick. In both the analysed cases the shell thickness increases by respectively $h_2 = 6$ cm and $h_2 = 3$ cm. After the strengthening had been made shear stresses on the surface denoted as 1–1 in Fig. 4, situated at the distance of respectively 6 and 3 cm from the cooling tower's outer surface, were determined.

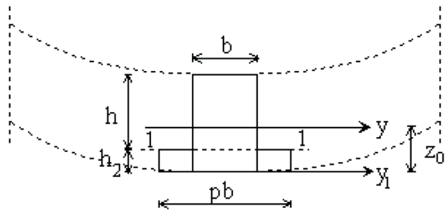

Fig. 4 Strengthened cooling tower shell model for determining shear stresses at interface between two materials

4.1 Analysis of shear stress at interface between materials for strengthening thickness of 6 cm

The increase in shear stress due to the use of a material with a higher E-modulus to strengthen the cooling tower shell is slightly larger when shell thickness is increased in comparison with the previous results for the repair with no change in shell thickness. For example, compare the results for the case when shell thickness is increased by 3 cm (Tables 15, 16 and 17) with the results for the case when the material is replaced, but shell thickness remains unchanged. The same tendency is observed when the results for shell thickness increased by 6 cm (Tables 7, 8 and 9) are compared with the results for the case when the material is replaced, but shell thickness remains unchanged (Tables 4, 5 and 6). However, one should bear in mind that in the case of a repair, the shell thickness is the same as the design shell thickness, whereas in the case of strengthening, it is larger than the design thickness.

Tables 7, 8 and 9 give us an idea about the increase in shear stress in the particular areas, while the next tables (beginning with Table 10) provide information on the increase in shear stress relative to the highest shear stress values occurring in the cooling tower shell.

The values given in Tables 7, 8 and 9, showing the increase in shear stress, are absolute values calculated for the particular cooling tower shell levels. It cannot be deduced from them whether the largest increase in stress

Table 7 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for 6 cm thick layer sprayed on shell of 132 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
8	72	1.069	1.196	1.308	1.410
15	48	1.056	1.156	1.243	1.318
22	24	1.029	1.077	1.116	1.146
68	20	1.022	1.056	1.082	1.103
128	20	1.022	1.056	1.082	1.103
129	26	1.033	1.087	1.130	1.166
132	32	1.041	1.111	1.169	1.217

Table 8 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 6 cm and 100 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
5	46	1.054	1.152	1.235	1.308
30	18	1.017	1.044	1.063	1.078
100	18	1.017	1.044	1.063	1.078

Table 9 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for replaced material thickness of 6 cm and 66.5 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/τ at $p = 1.1$	τ_1/τ at $p = 1.3$	τ_1/τ at $p = 1.5$	τ_1/τ at $p = 1.7$
3.5	36	1.046	1.124	1.191	1.247
11.5	21.2	1.024	1.063	1.093	1.116
13.5	19.2	1.020	1.051	1.075	1.093
15.5	18	1.017	1.044	1.063	1.078
66.5	18	1.017	1.044	1.063	1.078

occurs in the zone of the highest absolute shear stress values or perhaps in the zone where shear stress values are low. Fuller information is obtained by relating the determined stress values to the maximum stresses occurring in the shell of the considered cooling tower. Appropriate calculations were performed, gaining independence of the shear force values by dividing the stresses by the shear force.

Selected calculated ratios τ_1/T and τ/T are presented in the next tables. For example, the ratios calculated for the 132 m high cooling tower, taking into account the overall thickness of the shell + the shotcrete layer, are shown in the third and fourth column in Table 10. Then the values in columns 3 and 4 were normalized. The results of the normalization were entered into respectively columns 5 and 6.

The highest shear stress values in relation to the lateral force values occur from level +68 to level +128 m, i.e., in the part of the cooling tower shell where its thickness is the smallest. Column 7 in Table 10 shows normalized τ_1/τ ratio values (obtained by dividing the values contained in column 6 by the ones contained in column 5). In this way the normalized shear stress increases at the interface between the native material and the shotcrete sprayed onto the cooling tower shell were determined. The normalized shear stress increase values are lower than the analogous absolute stress increase values shown in Table 7.

Column 8 in Table 10 contains the products of the normalized τ_1/T values (column 6) and the τ_1/τ increases shown in Table 7. In this way the normalized stress increases in relation to the maximum stresses occurring in the cooling tower were determined.

Thus the relative values of the stresses increased due to the difference between the E-modulus values were obtained. The values were collated for the particular heights in relation to the maximum stresses occurring in the height interval of +68 m to +128 m. They can be interpreted as follows. The value of 0.113 given in column 8 in Table 10, corresponding to height $H = 8$ m, shows what fraction of the maximum shear stresses occurring in this cooling tower constitute the shear stresses occurring on level +8 m. This value was obtained by multiplying the value of 0.106 in column 6 of this table and the value of 1.069 in column 3 of Table 7, corresponding to $p = 1.1$. In the next tables only the columns showing the increase in stress τ_1 were left and so in Table 11 column 3 corresponds to column 4 of Table 10 and the appropriate column 4 corresponds to column 6 while column 5 corresponds to column 8. The other tables showing other values of coefficient p were constructed similarly as Table 11.

Sometimes the absolute stress increases are very large (amounting to, e.g., +8 m; at $p = 1.7$ the increase amounts to 41%, see Table 7), but relative to the highest shear stress values, they amount to merely 18.2% (see column 5, row 1 in Table 12) of the maximum stresses occurring in the height range of +68 m to +128 m.

Table 10 Normalized shear stresses and normalized shear stress increases for thickness increased by 6 cm by spraying shotcrete onto cooling tower shell, at coefficient $p = 1.1$ and cooling tower height of 132 m

1	2	3	4	5	6	7	8
H [m]	$h + h_2$ [cm]	τ/T at $p = 1.1$	τ_1/T at $p = 1.1$	Norm. τ/T	Norm. τ_1/T	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
8	72	0.0064	0.0068	0.101	0.106	1.047	0.113
15	48	0.0137	0.0144	0.217	0.224	1.032	0.237
22	24	0.0469	0.0482	0.744	0.750	1.008	0.766
68	20	0.0630	0.0644	1	1	1	1.022
128	20	0.0630	0.0644	1	1	1	1.022
129	26	0.0410	0.0423	0.650	0.657	1.011	0.679
132	32	0.0286	0.0297	0.453	0.462	1.019	0.481

The values in column 5 should be interpreted as follows: a value lower than the unity means that at the given height the shear stress (even if it increased) does not exceed the maximum values which occur in the interval of +68 m to +128 m. This means that a value lower than the unity certainly will not breach the shear strength condition. If, however, this value is higher than the unity, the shear strength within the evaluated interval is inadequate.

It emerges from the tables (Table 10 – column 8 and Tables 11–12 – column 5) that in the interval of +68 m +128 m, where shell thickness is smallest (amounting to 14 cm in the considered case) there occur the largest shear stress exceedances, amounting to 2.2–10.23% at respectively $p = 1.1$ and $p = 1.7$. Since exceedances (2.2–10.23%) occur at level +68 m, decreasing downwards, in each of the considered cases they will still occur in a certain area below level +68 m.

The above calculation results indicate that detailed analyses of strengthening with an additional material are needed for the cooling tower's part in which the smallest shell thickness occurs (here between +68 m and +128 m) and in the interval of +22 m to +68 m in areas where the normalized stress increases relative to the maximum stresses exceed the unity. It sometimes happens that strengthening is needed in these areas (especially in the tower throat). Then one should select a proper shotcrete for this purpose, i.e., one whose E-modulus is the same or closest to that of the native material.

In the lower cooling towers (Tables 13 and 14) shear stress exceedances are smaller than in the 132 m high cooling tower. In the considered two cases (100 m and 66.5 m high cooling towers), the minimal cooling tower thickness is the same, amounting to 12 cm, whereby the exceedances are always the same.

Table 11 Normalized shear stresses and normalized shear stress increases for thickness increased by 6 cm by spraying shotcrete onto cooling tower shell, at coefficient $p = 1.3$ and cooling tower height of 132 m

1	2	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.3$	Norm. τ_1/T	(Norm. $\tau_1/T)(\tau_1/\tau)$
8	72	0.0076	0.114	0.137
15	48	0.0158	0.238	0.275
22	24	0.0505	0.759	0.818
68	20	0.0665	1	1.056
128	20	0.0665	1	1.056
129	26	0.0445	0.669	0.728
132	32	0.0317	0.477	0.530

4.2 Analysis of shear stress at interface between materials for strengthening thickness of 3 cm

As part of cooling tower renovations the cooling tower shell is often covered with a thin layer of unreinforced shotcrete. This layer is usually less than 3 cm thick. Tables 15–20 below show similar calculation results as for thickness $h_2 = 3$ cm.

More general conclusions emerge from an analysis of the values contained in columns 5 of Table 18. And so when the shell is strengthened with a 6 cm thick shotcrete layer, the increase in shear stress in the zones situated below level +22 m and above level 128 m will be larger than when the shell is strengthened with a 3 cm thick layer. In the interval from +22 m to +128 m a larger increase in shear stress occurs when the cooling tower shell is strengthened with a 3 cm thick shotcrete layer. The increase is significant, amounting to 4.4% at $p = 1.1$ and to 23.3% at $p = 1.7$. The above values are for unreinforced shotcrete sprayed onto the native concrete. This means that interaction between the two materials can be ensured through the use of suitable bond layers or connectors. When selecting the latter, one should take into account the calculated increase in shear stress.

Table 12 Normalized shear stresses and normalized shear stress increases for thickness increased by 6 cm by spraying shotcrete onto cooling tower shell, at coefficient $p = 1.5$ and $p = 1.7$ cooling tower height of 132 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.5$	Norm. τ_1/T	(Norm. $\tau_1/T)(\tau_1/\tau)$	τ_1/T at $p = 1.7$	Norm. τ_1/τ	(Norm. $\tau_1/T)(\tau_1/\tau)$
8	72	0.0083	0.122	0.160	0.0090	0.129	0.182
15	48	0.0170	0.249	0.310	0.0180	0.259	0.342
22	24	0.0523	0.767	0.856	0.0537	0.773	0.886
68	20	0.0682	1	1.082	0.0695	1	1.103
128	20	0.0682	1	1.082	0.0695	1	1.103
129	26	0.0463	0.679	0.768	0.0478	0.687	0.801
132	32	0.0334	0.490	0.573	0.0348	0.501	0.609

Table 13 Normalized shear stresses and normalized shear stress increases for thickness increased by 6 cm by spraying shotcrete onto cooling tower shell, at all considered coefficients p and cooling tower height of 100 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.1$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at $p = 1.3$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)
5	46	0.0156	0.2072	0.219	0.0170	0.220	0.253
30	18	0.0753	1	1.017	0.0773	1	1.044
100	18	0.0753	1	1.017	0.0773	1	1.044
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.5$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at $p = 1.7$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)
5	46	0.0183	0.232	0.287	0.0193	0.242	0.316
30	18	0.0788	1	1.063	0.0799	1	1.078
100	18	0.0788	1	1.063	0.0799	1	1.078

Table 14 Normalized shear stresses and normalized shear stress increases for thickness increased by 6 cm by spraying shotcrete onto cooling tower shell, at all considered coefficients p and cooling tower height of 66.5 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.1$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at $p = 1.3$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)
3.5	36	0.0242	0.321	0.336	0.0260	0.337	0.379
11.5	21.2	0.0588	0.781	0.800	0.0610	0.789	0.839
13.5	19.2	0.0685	0.909	0.927	0.0706	0.913	0.960
15.5	18	0.0753	1	1.017	0.0773	1	1.044
66.5	18	0.0753	1	1.017	0.0773	1	1.044
H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.5$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at $p = 1.7$	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)
3.5	36	0.0276	0.350	0.417	0.0289	0.362	0.451
11.5	21.2	0.0628	0.797	0.871	0.0641	0.802	0.895
13.5	19.2	0.0722	0.916	0.985	0.0734	0.920	1.006
15.5	18	0.0788	1	1.063	0.0799	1	1.078
66.5	18	0.0788	1	1.063	0.0799	1	1.078

Table 15 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for 3 cm thick shotcrete layer sprayed onto shell of 132 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.1$	τ_1/T at $p = 1.3$	τ_1/T at $p = 1.5$	τ_1/T at $p = 1.7$
8	69	1.082	1.239	1.387	1.526
15	45	1.074	1.212	1.339	1.454
22	21	1.052	1.142	1.219	1.285
68	17	1.044	1.118	1.180	1.233
128	17	1.044	1.118	1.180	1.233
129	23	1.055	1.152	1.235	1.308
132	29	1.062	1.175	1.274	1.362

The tendencies are the same in the case of the other two cooling towers, but the values of the considered quantities are lower. The fact that values higher than 1 are in the thinnest part of each of the cooling towers means that normalized stress increases are also exceeded in a certain area in the thicker part.

Table 16 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for 3 cm thick shotcrete layer sprayed onto shell of 100 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.1$	τ_1/T at $p = 1.3$	τ_1/T at $p = 1.5$	τ_1/T at $p = 1.7$
5	43	1.073	1.209	1.333	1.446
30	15	1.039	1.104	1.157	1.201
100	15	1.039	1.104	1.157	1.201

Table 17 Increase in shear stress at interface between materials, expressed by ratio τ_1/τ, for 3 cm thick shotcrete layer sprayed onto shell of 66.5 m high cooling tower, ($p = E_1/E$)

H [m]	$h + h_2$ [cm]	τ_1/T at $p = 1.1$	τ_1/T at $p = 1.3$	τ_1/T at $p = 1.5$	τ_1/T at $p = 1.7$
3.5	33	1.066	1.187	1.295	1.391
11.5	18.2	1.046	1.126	1.193	1.250
13.5	16.2	1.042	1.113	1.171	1.221
15.5	15	1.039	1.104	1.157	1.201
66.5	15	1.039	1.104	1.157	1.201

Table 18 Normalized shear stresses and normalized shear stress increases for thickness increased by 3 cm by spraying shotcrete onto cooling tower shell, at all considered coefficients p and cooling tower height of 132 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.1	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.3	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
8	69	0.0039	0.073	0.079	0.0045	0.078	0.097
15	45	0.0089	0.167	0.179	0.0101	0.175	0.213
22	21	0.0368	0.687	0.723	0.0340	0.697	0.796
68	17	0.0535	1	1.044	0.0574	1	1.118
128	17	0.0535	1	1.044	0.0574	1	1.118
129	23	0.0312	0.583	0.615	0.0341	0.594	0.684
132	29	0.0204	0.381	0.405	0.0226	0.393	0.462
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.5	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.7	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
8	69	0.0050	0.083	0.115	0.0055	0.087	0.133
15	45	0.0111	0.183	0.246	0.0121	0.191	0.278
22	21	0.0427	0.704	0.859	0.0450	0.711	0.914
68	17	0.0605	1	1.180	0.0632	1	1.233
128	17	0.0605	1	1.180	0.0632	1	1.233
129	23	0.0366	0.604	0.746	0.0387	0.612	0.800
132	29	0.0245	0.404	0.499	0.0055	0.087	0.133

Table 19 Normalized shear stresses and normalized shear stress increases for thickness increased by 3 cm by spraying shotcrete onto cooling tower shell, at all considered coefficients p and cooling tower height of 100 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.1	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.3	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
5	43	0.0097	0.146	0.157	0.0109	0.154	0.187
30	15	0.0665	1	1.039	0.0706	1	1.104
100	15	0.0665	1	1.039	0.0706	1	1.104
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.5	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.7	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
5	43	0.0121	0.163	0.218	0.0131	0.170	0.246
30	15	0.0741	1	1.157	0.0769	1	1.201
100	15	0.0741	1	1.157	0.0769	1	1.201

Table 20 Normalized shear stresses and normalized shear stress increases for thickness increased by 3 cm by spraying shotcrete onto cooling tower shell, at all considered coefficients p and cooling tower height of 66.5 m

1	2	3	4	5	3	4	5
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.1	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.3	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
3.5	33	0.0160	0.241	0.257	0.0178	0.252	0.300
11.5	18.2	0.0475	0.714	0.747	0.0511	0.724	0.815
13.5	16.2	0.0582	0.875	0.911	0.0622	0.881	0.980
15.5	15	0.0665	1	1.039	0.0706	1	1.104
66.5	15	0.0665	1	1.039	0.0706	1	1.104
H [m]	$h + h_2$ [cm]	τ_1/T at p = 1.5	Norm. τ_1/T	(Norm. τ_1/T)(τ_1/τ)	τ_1/T at p = 1.7	Norm. τ_1/τ	(Norm. τ_1/T)(τ_1/τ)
3.5	33	0.0195	0.263	0.341	0.0209	0.272	0.378
11.5	18.2	0.0541	0.730	0.871	0.0567	0.738	0.922
13.5	16.2	0.0655	0.884	1.036	0.0682	0.887	1.083
15.5	15	0.0741	1	1.157	0.0768	1	1.201
66.5	15	0.0741	1	1.157	0.0768	1	1.201

The relative values collated in the tables (starting from Table 7) were calculated with no shear force taken into account. When developing detailed cooling tower strengthening designs one should take into account the shear forces in the whole cooling tower and the actual E-moduli of respectively the native material and the material intended for cooling tower strengthening. Such calculations will show whether the shear stresses occurring at the interface between the two materials are higher or lower than the shear strength.

5 Conclusions

In this paper, an analysis of the stress state at the interface between the different materials was carried out. Shear stress increases were found to occur at the interface between the materials differing in their specifications.

Detailed analysis showed that the largest increase in shear stress in relation to the maximum shear stresses present in the considered cooling towers occurs in the thinnest shell zones. Since the minimal thickness predominates along the cooling tower height, a potential hazard of failure exists over the predominant area of the cooling tower. The largest absolute increases in shear stress occur in the cooling tower's lower area where shell thickness is larger than the cooling tower's minimal shell thickness and in its crown zones where shell thickness increases.

The use of a repair (strengthening) material differing in its specifications from the native material can result, due to shear strength loss, in the independent existence of the two parts (the repair material is debonded from the native material). Debonding usually increases the system's susceptibility to corrosion.

Considering that shear stresses increase at the interface between materials differing in their specifications, this fact should be taken into account in cooling tower load-bearing capacity calculations. It would be best if the repair materials' specifications were closest to or ideally, identical with those of the native material.

References

[1] Martin, R. "Substantial Concrete Repair of two Cooling Towers of the TOTAL Refinery in Leuna, Germany", In: Harte, R. (ed.) ICCT 2014, International Conference on Industrial Chimneys & Cooling Towers, Prague, Czech Republic, 2014, pp. 341–350.

[2] Knight, B. "Assessment and repair of delaminated concrete mantels to cooling towers in East Midlands, England", In: Harte, R. (ed.) ICCT 2012, 6th International Conference on Industrial Chimneys & Cooling Towers, Cologna, Germany, 2012, pp. 521–528.

[3] Lechman, M. "Structural assessment and repair of a tall RC chimney", In: Harte, R. (ed.) ICCT 2016, International Conference on Industrial Chimneys and Cooling Towers, Edinburgh 2019, Rotterdam, Netherlands, 2019, pp. 249–256.

[4] Pfister, T., Scharf, H., Siegert, U., Reschminski, K., Fickler, N., Lehnen, D. "A Cooling Tower in Eight Pieces - Calculation and repair of a heavily damaged shell structure", In: Harte, R. (ed.) ICCT 2016, International Conference on Industrial Chimneys and Cooling Towers, Edinburgh 2019, Rotterdam, Netherlands, 2019, pp. 329–336.

[5] Eastman, G., Goddard, C., Lohr, R. "Repairs to and rebuilding of a 122m high natural draught cooling tower on the US East Coast", In: Harte, R. (ed.) ICCT 2016, International Conference on Industrial Chimneys and Cooling Towers, Edinburgh 2019, Rotterdam, Netherlands, 2019, pp. 95–102.

[6] Bamu, P. C., Zingoni, A. "Damage, deterioration and the long-term structural performance of cooling-tower shells: A survey of developments over the past 50 years", Engineering Structures, 27, pp. 1794–1800, 2005.
https://doi.org/10.1016/j.engstruct.2005.04.020

[7] Kulkarni, S., Hosur, V. I. "Review on Modeling of hyperbolic cooling towers", International Journal of Scientific & Engineering Research, 9(1), pp. 387–399, 2018.

[8] Anyi, J. N., Nzengwa, R., Amba, J. C., Ngayihi, C. V. A. "Approximation of linear elastic shells by curved triangular finite elements based on elastic thick shells theory", Mathematical Problems in Engineering, 2016, 8936075, 2016.
https://doi.org/10.1155/2016/8936075

[9] Fulzele, P. M., Prasad, R. V. R. K. "Review on: Construction Technique of Hyperbolic Cooling Tower", International Journal of Innovations in Engineering and Science, 5(9), pp. 11–18, 2020.
https://doi.org/10.46335/IJIES.2020.5.9.2

[10] Beushausen, H., Alexander, M. G. "Bond strength development between concretes of different ages", Magazine of Concrete Research, 60(1), pp. 65–74, 2008.
https://doi.org/10.1680/macr.2007.00108

[11] Halicka, A. "A study of the stress-strain state in the interface and support zones of composite structures with shrinkable and expansive concretes", Lublin University of Technology, 2007. (in Polish)

[12] Halicka, A., Franczak-Balmas, D. "O efekcie skali w jednorodnych i zespolonych elementach betonowych. Cz. 2, Badanie efektu skali w pomiarze przyczepności betonu "starego" i "nowego" metodą rozłupywania", (The size effect in monolithic and composite concrete members. Part II: the examination of size effect by adhesion measurement of "old" and "new" concrete using splitting tensile test), Cement Wapno Beton, 19(4), pp. 262–266, 2014.

[13] Halicka, A., Jabłoński, Ł. "Shear failure mechanism of composite concrete T-shaped beams", Proceedings of the Institution of Civil Engineers - Structures and Buildings, 169(1), pp. 67–75, 2016.
https://doi.org/10.1680/stbu.14.00127

[14] Vaysburd, A., Bissonnette, B., Garbacz, A., Courard, L. "Specifying Concrete Repair Materials", Materiały Budowlane, 523(3), pp. 42–45, 2016.
https://doi.org/10.15199/33.2016.03.13

[15] Courard, L. "Parametric study for the creation of the interface between concrete and repair products", Materials and Structures, 33, pp. 65–72, 2000.
https://doi.org/10.1007/BF02481698

[16] Santos, P. M. D., Santos Júlio, E. N. B. "Factors Affecting Bond between New and Old Concrete", ACI Materials Journal, 108(4), pp. 449–456, 2011.

[17] Sadowski, G., Wiliński, P., Halicka, A. "Analysis of the shear resistance in the indented interface between two concrete parts of concrete composite beam", Civil and Environmental Engineering Reports, 31(1), pp. 93–105, 2021.
https://doi.org/10.2478/ceer-2021-0007

[18] Kang, J.-Y., Park, J.-S., Jung, W.-T., Keum, M.-S. "Shear Behavior in Indented Concrete Layers with Different Strengths", Engineering, 8(7), pp. 423–431, 2016.
https://doi.org/10.4236/eng.2016.87039

[19] Wang, B., Xu, S., Liu, F. "Evaluation of tensile bonding strength between UHTCC repair materials and concrete substrate", Construction and Building Materials, 112, pp. 595–606, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.02.149

[20] Islam, M. R., Habib, M. Z. "Strength between Old and New Concrete", International Journal of Scientific & Engineering Research, 7(1), pp. 383–386, 2016.

[21] Bissonnette, B., Vaysburd, A. M., von Fay, K. F., Harrell, S. H., Courard, L., Garbacz, A. "Concrete substrate moisture requirements for durable concrete repairs – a field study", MATEC Web of Conferences, International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2022), 364, 04006, 2022).
https://doi.org/10.1051/matecconf/202236404006

[22] Garbacz, A., Górka, M., Courard, L. "Effect of concrete surface treatment on adhesion in repair systems", Magazine of Concrete Research, 57(1), pp. 49–60, 2005.
https://doi.org/10.1680/macr.2005.57.1.49

[23] Courard, L., Piotrowski, T., Garbacz, A. "Near-to-Surface properties affecting bond strength in concrete repair", Cement and Concrete Composites, 46, pp. 73–80, 2014.
https://doi.org/10.1016/j.cemconcomp.2013.11.005