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Analysis on the Mechanism of Difference in Cracking of Super-Long Basement

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The problem of super-long basement cracking is very common in engineering, and exist obvious differences in various part. Based on the analysis of relevant parameters in the practical calculation formula of temperature stress, this paper analyzed the different cracking mechanism of the baseboard, external walls and baseboard from the qualitative perspective, then explains its inner causes from the aspects of environment conditions, horizontal resistance coefficient and the size effect to help the designer and construction technician to determine the weak lines in anti-cracking and the construction precautions, thereby, improving the qualities of design and construction.

1. Introduction

Generally, the super-long basement bears a large integrated temperature differences like hydration heat temperature difference, shrinkage equivalent temperature difference and production heat distribution temperature difference, however, compared with ground building structure, the basement bears a relative smaller temperature differences. In engineering, it often choosing some technical measures like using the preferred materials, better curing conditions, strengthens the reinforcement of weak links and post-cast strip to avoid cracking. According to a large number of engineering practices, although the baseboard, external wall and roof are buried under ground, there exist great cracking differences in form and probability. Among them, most flexible waterproof of the baseboard is cancelled actually and only reinforced concrete structure self-waterproofing, while the external walls and roof have both; In addition, the baseboard is deeper with much larger groundwater pressure and socked in groundwater longer. Logically, the leakage rate of the external wall and roof should be lower than baseboard, but, the actual situation is widely divergent to this conclusion. It is found that the highest probability of cracking is the roof and external walls; the probability of the external walls is 65% to 85%, while the baseboard is about 20% (Wang, 2007). This paper intends to make internal mechanism analysis on the crack factors, clarify the root causes of differences, so that the anti-crack design will be more targeted and effective, adding more content for the “anti-crack concept design”, and put forward related precautions for design and construction accordingly (Macedo et al., 2017).

2. Analysis on the influencing factors of cracking under deformation

2.1 Practical calculation formula of temperature stress

The shrinkage caused by the temperature difference in baseboard, roof and external walls is restrained and produced external stress, which is called temperature stress, and it is the main cause of penetration cracks. Professor Wang Tiemeng, a well-known crack control expert, based on a large number of engineering practice and field research, combined with the mechanics theory, analyzed and deduced the theoretical formula of the temperature stress at different locations (x- the midpoint of the component as the origin) and the maximum temperature stress in one-way constraint and one-dimensional, the formula is as follow (Wang, 2007):

$$\sigma_x = -E\alpha T\left(1-\frac{\cosh \beta x}{\cosh(\beta \frac{L}{2})}\right)H(t,\tau) \tag{1}$$

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$$\sigma_{x\max} = -E\alpha T(1 - \frac{1}{\cosh(\beta \frac{L}{2})})H(t,\tau) \tag{2}$$

E-elastic modulus of concrete; α- linear expansion coefficient; $H(t,\tau)$ - stress relaxation coefficient;
-the length of board or wall; T - integrated temperature difference, including hydration heat temperature difference, shrinkage equivalent temperature difference, the production heat distribution temperature difference and the temperature difference;

The parameter $\beta = \sqrt{\frac{C_x}{HE}}$

C_x -foundation horizontal resistance coefficient; H-the thickness of baseboard and roof or the height of external walls

Considering the baseboard and roof belongs to two-way constraint and two-dimensional stress, the above formula should be divided by (1~μ), for the Poisson ratio, the reinforced concrete structure, μ is desirable between 0~0.1, using the median value 0.05 in following calculation.

Based on the practical calculation formula of the temperature stress, the engineering community has solved many non-load crack control problems of large volume concrete engineering and large basement (Wang, 2007; Xu and Xu, 2012). In this paper, the relevant parameters of the practical formula are analyzed to clarify the internal mechanism of the difference in the cracking of different parts.

2.2 Analysis of the internal mechanism of the difference in basement cracking

Analyzing the causes of shrinkage cracks and a number of parameters in the temperature stress calculation formula helps us to find out why the cracking rate of floor is much smaller than external walls and roof.

The first one is the impact of humid environments. Due to the flexible waterproof layer is often cancelled in engineering, thus the baseboard is in a humid environment since the construction period. Table 1 shows the tensile strength and ultimate stretching data of the same kind of concrete in static load test under different conservation conditions (Wang, 2007).

Table 1: Tensile strength and ultimate stretching

Conservation conditions	Tensile strength f_t (Mpa)	Ultimate stretching ε_t (10^{-5})
Dry	0.69	6.1
Damp	1.40	8.0
Water	1.63	9.0

It can be seen from Table 1 that the tensile strength and ultimate stretching capacity of concrete in water and humid environments are much higher than that in dry environment. And table 1 is static load test data, considering the deformation is a slow process, accompanied with a larger creep, and a well moisturizing concrete will have better creep abilities due to homogeneity. That is, considering the ultimate stretch after the creep [$\varepsilon_{p.a}$], on the basis of static load test, the difference will be further expanded, which will bring greater temperature stress relaxation. In better moisturizing conditions, the general stress relaxation coefficient $H(t,\tau)$ can take 0.3, 0.5 under normal conditions, and 0.8~1 (Wang, 2007) in sudden cooling and drastic conditions. It means baseboard humid conservation not only has greater tensile strength f_t, but also lower stress relaxation coefficient $H(t,\tau)$. Second, the shrinkage of concrete in humid soil tends to 0 without considering the thermal expansion, and slightly inflated in water. Therefore, for self-waterproof structure, the baseboard is unlikely to crack or leakage. This mechanism has certain guiding significance to construction, indicating that the precipitation does not make soil the dryer the better, and avoiding dry state in a long-term after the baseboard is finished. In the premise of ensuring anti-floating safety, the basement baseboard should in a good state of water conservation, which is favorable to prevent cracking.

It is also being mentioned that humid conservation is benefit to permanently improve the self-waterproof ability of baseboard. Although the flexible waterproof structure has greater deformation capacity than the self-waterproof structure, most of current waterproof construction is difficult to ensure no leakage at all, materials or construction quality defects often lead to local leakage, resulting in flexible waterproof layer was broken and lose its function, and the evidence is that many flexible waterproof external walls and roof have leakage problems. Even if the construction quality is guaranteed, the flexible waterproof material still exist aging problem with about 10-20 years of durability period, and its bottom layer is irreplaceable. Thus, improving the structure self-waterproof capacity is the basis to ensure waterproof quality. While the external walls and roof are different, their conservation conditions are no better than baseboard, needing multi-channel waterproof, thus, the flexible waterproof layer of these two parts has a certain interchangeability and easy to repair. Therefore, is there exists an idealized problem that in certain circumstances, the basement baseboard plus flexible waterproof will permanently improve the waterproof effect? Whether it worth or not? It is necessary to conduct a systematic comparative study on the advantages and disadvantages of baseboard flexible waterproof. Under certain circumstances, it should be analyzed under different geological conditions rather than the current one-size-fits-all request.

Then is the impact of environmental temperature difference. Generally, the hydration heat maximum temperature and the minimum ambient temperature difference are regarded as the integrated temperature difference T. As the long construction period, the basement roof does not have insulation conditions but exposed outside directly in cold season, and the actual temperature is the roof temperature. While the baseboard is buried deeper, and more affected by lower ground temperature rather than the actual temperature. According to the results of ground temperature research (Xu, 2012), the depth 3m below the ground does not affected by daily temperature changes, it’s only affected by annual temperature wave amplitude, the deeper the embedded, the smaller the temperature amplitude. Generally, the basement depth is far more than 3m, and the multi-layer basement often have tens of meters buried depth, the minimum stable temperature of baseboard is close to the average annual temperature. Even if the top of the baseboard, the inside temperature is also relatively higher. Therefore, with a largest temperature-rise, the directly exposed roof will form a larger integrated temperature difference, and a larger cracking rate during the cold season is proof. In addition, the roof is also more susceptible to the sudden drop in temperature, due to the concrete cannot produce large creep in a short time, thus the stress relaxation will be smaller, $\mathrm{H}(\mathrm{t},\tau)$ is desirable in 0.8~1, much larger than the normal 0.5, according to the formula (2), compared with the slow cooling, the sudden temperature drop will result greater σ_{xmax}. From this mechanism, we can see that the focus of winter construction is to ensure the insulation conservation work, to prevent the rapid changes in temperature. In addition, when the cooling and shrinkage occurs at the same time, the concrete will be subjected to mutual tension and easier to crack, therefore, with a higher temperature, the construction in summer is easier to crack than in spring and winter, theoretically, the super-long basement and mass construction should carry on when the relative temperature is slow.

The impact of air-dry and sunshine cannot be ignored. Large basement baseboard is generally buried deeply, in a relatively static environment. Compared with the roof, the wind speed is smaller and single-side affected, and the baseboard is not easy to dehydration or shrinkage. After the construction is finished, the baseboard is unaffected by air and avoid sun exposure, the humid conservation is convenient in maintaining moisture, reduced the shrinkage caused by water evaporation and bleeding. The concrete crack phenomenon in engineering in the condition of dehydration exposure, wind and sun does not occur in baseboard. Based on this mechanism, in the late term of construction, it should be fill back as soon as possible, which can play a good conservation effect, if do not have the covering conditions, the key is to focus on roof moisturizing conservation in summer (Guo, 2008).

The next one is the foundation horizontal resistance coefficient C_x. The temperature stress belongs to constraint stress, as the name implies, it produced by the constraint of boundary conditions, the larger the constraint, the greater the stress will be. The baseboard is poured firstly, and if there is no restraint of foundation soil, it will be free to stretch without any temperature stress. But it is inevitably affected by the constraints of foundation soil and produces a certain temperature stress (Guo, 2009). Therefore, the temperature stress level of the baseboard is closely related to the horizontal resistance coefficient C_x, which is show in table 2 when restrained by various foundations. The constraints type of baseboard external walls and roof are different. The shrinkage and deformation of baseboard are restrained by the foundation soil, and the soft clay C_x is the smallest, non-weathered rock C_x is larger, so the cracking risks of different foundation soil are quite different. External walls are subject to the pre-pouring baseboard constraints, which is relatively larger, according to the formation mechanism of constraints, the more the baseboard is cured, the greater the time difference between the baseboard and the external wall, and the greater the relative restraint; the thicker the baseboard, the greater the constraint on the external walls. This is the one architect should pay attention to, many structural designs often arrange large base beams in the junction parts to strengthen the structure, which is unnecessary (because the in-plane stiffness of the reinforced concrete external walls is sufficient, there is no need to carry out redundant structural reinforcement), on the contrary, it’s more easily lead to restraint stress. The constraints of roof can be divided into two parts to discuss: the local plate is bound by the frame beam around, and C_x is larger; the whole roof is supported and constraint by its lower frame column and shear wall, and the fixed restraint of external walls. The constraint size is related to the horizontal stiffness of column net and shear wall arrangement, the larger the spacing the smaller the C_x; meanwhile it bears fixed constraints of the surrounding external walls, the constraint size associated with wall’s distribution. According to the above analysis, the C_x of various foundation soil are different, and has a greater impact on temperature stress, a large number of facts show that strong constraint on baseboard made it easier to crack, which proves the correctness of this mechanism (Wang, 2007). The guiding significance on design and construction is that in the foundation soil with large C_x pouring large area of baseboard should set slide layer for anti-crack, including asphalt sand cushion, gravel cushion, etc. which can play a certain role in isolation and softening constraints (Wang, 2007); in the junction parts, the baseboard size should not be too large than just, otherwise produce a strong constraint on the post-cast external walls and resulting crack.

Table 2: Foundation horizontal resistance coefficient C_x

Foundation soil and restraint surface	Horizontal resistance coefficient（Mpa/mm）
Soft clay	0.01~0.03
General sandy clay	0.03~0.06
Especially hard clay	0.06~0.10
Weathered rock, low-labeled concrete	0.60~1.00
Non-weathered rock, the reinforced concrete above C_{10}	1.00~1.50
Steel concrete beam pouring baseboard	0.60~1.00

The effect of size effect should also be concerned. In a basement without body building on the ground, its thickness is at least 400~500mm, and the common thickness of first layer roof and external walls is between 250~350mm. According to the dry shrinkage mechanism, the shrinkage is caused by evaporation and bleeding inside the concrete, the volume shrink is always from table to inside, which means the shrinkage occurs mainly in the concrete surface, which has certain size effect. The entire cross section of the thinner members is susceptible to shrinkage, while the cross-section in the relatively thicker section almost no shrinkage, and plays a certain role in blocking surface shrink. Secondly, according to σ_{xmax} formula (2), the parameter β we can know that the thicker the component, the smaller β and σ_{xmax}, which is benefit to anti-crack. Thirdly, under certain C_x conditions, if the baseboard is relatively thicker, the greater the total shrinkage force, the smaller the relative restraint resistance of foundation soil, and the contraction is relatively free, so that when the baseboard is finished, certain degree of free shrinkage can be produced to release restraining stress. In addition, for the ground part, baseboard size effect is also confirmed. Many practical projects found that the thinner the residential baseboard, the easier to cracking, therefore, the appropriate thickening of baseboard in structural design is conducive to crack prevention.

3. Calculation examples of maximum temperature stress

The strength grade, composition, construction, maintenance, constraint conditions and others of the concrete materials are different, making the relevant parameters in the temperature stress calculation formula have great discrepancy. The following calculation examples select relevant parameters according to common situation and made a considerable simplification in order to obtain quantitative comparison conclusion of the difference among the floor, external walls and the roof.

3.1 Calculation of the maximum temperature stress

Some parameters of the concrete materials are taken from the “Code for Design of Concrete Structures” GB50010-2010, using the unified intensity C35. Considering the early shrinkage stress is often released by post-cast strip in super-long basement, which the closure time is no less than 45 days, and the early temperature difference (hydration heat temperature difference and production heat distribution temperature difference) and about 60% shrinkage equivalent temperature difference has been completed (Xu and Xu, 2012). At this stage, the elastic modulus is small with great stress relaxation, and the floor segment is short, therefore the temperature stress is small in a proper conservation. For this reason, the temperature difference value in formula (2) using the values in second stage. Simplify the treatment to calculate and comparing, assuming that the roof does not have casing conditions in a long time with 25℃ integrated temperature difference, floor and external walls are taken 20℃. Other parameters are as follow: the floor thick take 0.5m, based on two-way constraints of two-dimensional plane stress, C_x take 0.06Mpa/mm and $\mathrm{H}(\mathrm{t},\tau)$ take 0.3; external walls height take 4m, based on one-way constraint of one-dimensional plane stress, C_x take 1.0Mpa/mm and $\mathrm{H}(\mathrm{t},\tau)$ take 0.4; roof take 0.3m thick, $\mathrm{H}(\mathrm{t},\tau)$ take 0.5 in two-dimensional plane stress state; the overall roof constraint depends on the horizontal stiffness of the frame column, take 0.006Mpa/mm in calculation examples, and the maximum value of overall temperature stress is σ_{1xmax}; local panel is bound by surrounding frame beam, the cross board take 7m, C_{1x} take the lower limit value 0.6Mpa/mm, local maximum temperature stress σ_{1xmax}=1.22Mpa, roof σ_{xmax}; is more safer and take the sum of σ_{1xmax}; and σ_{2xmax};. Substituting above parameters in formula (2), the σ_{xmax} under different length conditions can be calculated, as shown in table (3).

Table 3: Relations between maximum temperature stress and length on different parts

Length of board or wall L(m)	Maximum temperature stress of different parts (Mpa)		
	Floor	External wall	Floor
30	0.63	1.28	1.50
50	1.18	1.98	1.93
80	1.65	2.38	2.69
100	1.81	2.46	3.19
150	1.95	2.51	4.14
200	1.98	2.52	4.70
300	1.99	2.52	5.18

In the table, the σ_{xmax} in external walls and the roof is only a theoretical calculation, in practice, the temperature stress cannot exceed the tensile strength, and otherwise the concrete has long been cracked. Considering the shrinkage cracks do not affect its safety, the determination of cracking should be based on the standard value of concrete tensile strength, and the standard value of C35 concrete is 2.20Mpa. From table (3) we can learn that after a certain length, the roof is the easiest to crack, the external walls followed, and the floor do not crack in this calculation example, indicating that the temperature stress converges to a constant less than the concrete tensile strength.

3.2 Analysis of maximum temperature stress calculation results

The assumptions of above examples are quite particular and unsuitable to specific projects, but its conclusion has a guiding significance, helping us to establish the basic concept of "anti-crack concept design".
In the case of less restricted by foundation soil, due to unique environmental and conservation conditions, the general floor can achieve infinitely long without cracking theoretically. While for external walls and roof, there is a relatively large probability of cracking, especially the super-long one, which is inevitable even if set up post-cast strip and other measures.
According to the theory of temperature stress calculation, we learn that σ_{xmax} appeared in the middle of the board, when σ_{xmax} is exceed the concrete tensile strength, the board is cracked into two parts. The maximum temperature stress of sub-board will still appear in the middle, and the cracks should be very regular, which is inconsistent with actual situations, for example, in a 200m long basement, as long as there are three cracks, the basement can be divided into four 50m long sub-board, then, using chemical grouting technology to handling the three cracks can simply solve all super-long problems. According to the calculate results, when the length of the board is small, the temperature stress increases abruptly with the length, but when it is long and large, σ_{xmax} converges to a constant, resulting a large area near the midpoint in a higher temperature stress state and belongs to "crack risk zone". If the temperature drops rapidly, the temperature stress in a large area may simultaneously exceed the tensile strength. When the first crack appears, the temperature stress of the concrete near the cracks is instantaneously relaxed without cracking, on the contrary, due to the concrete creep relaxation is slow and the hindering effect of the foundation soil, the temperature stress has not been instantly relaxed, the place away from the first cracks may still cracking, thus the second, third …cracks appears within the "crack risk zone", their spacing are influenced by the amplitude and speed of sudden cooling, the larger the amplitude and the faster the cooling speed, the smaller the spacing, rather than regular constant division theoretically.
σ_x is proportional to the integrated temperature difference T. In the construction of super-long basement, it is necessary to take measures like post-cast strip to release the higher hydration heat temperature difference and shrinkage equivalent temperature difference in pre-period; otherwise the second stage after closure will form a larger integrated temperature difference. Therefore, the opportunity of post-cast strop should be carried out at a lower temperature, especially when the roof do not have casing conditions for a long time and withstand exposure and quench directly. The conservation work in summer should focus on moisturizing conservation, while in winter is insulation to prevent rapid temperature changes and dehydrated.
Whether the maximum temperature stress should be superimposed on the first stage $\boldsymbol{\sigma}'_{\mathbf{xmax}}$
before the closure of post-cast strip and the second stage $\boldsymbol{\sigma_{xmax}}$ after closure? Considering the concrete E and H(t, τ) is relatively small with short segments and $\boldsymbol{\sigma}'_{\mathbf{xmax}}$ value can be ignored. Meanwhile, generally $\boldsymbol{\sigma_{xmax}}$ and $\boldsymbol{\sigma}'_{\mathbf{xmax}}$ do not appears in the same position, $\boldsymbol{\sigma_{xmax}}$ is the actual maximum temperature stress. But if the space of post-cast strip is too large $\boldsymbol{\sigma}'_{\mathbf{xmax}}$ before closure will increased sharply, resulting the maximum temperature stress after closure increased either on the basis of $\boldsymbol{\sigma_{xmax}}$, and thus the space should not exceed 40m.
The $\boldsymbol{\sigma_{xmax}}$ calculation of roof should have superimposed on integral $\boldsymbol{\sigma_{1xmax}}$ and part $\boldsymbol{\sigma_{2xmax}}$, indicating the constraint stiffness mutation will produce additional temperature stress, which caused by shrinkage difference

of the deformation in section or subject to additional constraints (Guo, 2008). The additional temperature stress should be avoid and when it is inevitable, some measures should be taken to isolate and soften the restraint effect, such as set polystyrene foam veneer on the side of the floor deck to buffer horizontal resistance (Wang, 2007), or strengthen anti-cracking measures in the place exists thickness difference.

4. Conclusion

This paper analyzes the different cracking mechanism of roof, external wall and roof from the perspective of qualitative and quantitative. It clarified the underlying causes from different aspects like environmental conditions, foundation horizontal resistance coefficient and size effect. It simplified the temperature stress of the floor, the external walls and the roof under certain conditions, and analyzes their relationship from a quantitative perspective, proposed the “crack risk zone” and a number of designs, construction considerations, which has a good explanation for some cracking phenomena and regularity in practice engineering. The relevant conclusions and mechanism have certain practical significance for concrete projects, which can be used as an important content of “anti-crack concept design” in super-long basement, ensure the anti-crack design being more targeted and aware of the weak lines, making suitable adjustments according to corresponding mechanism.

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Reference

Guo J., 2008, Crack control and corresponding technical measures for super-long concrete structures, Building Science, 24(11), 90-93.

Guo J., Yang Y., Liu X., 2009, Analysis on some design factors of cast pouring board cracking, Sichuan Building Science, 35(4), 105-107.

Macedo Neto J., Kimura S.P.R., Vieira M.G.A., Neto J.E., Nascimento N.R., Lona L.M.F., 2017, Intercalation and exfoliation mechanism of kaolinite during the emulsion polymerization, Chemical Engineering Transactions, 57, 1453-1458, Doi: 10.3303/CET1757243.

Wang T., 2007, Control of Cracking in Engineering Structure Principle of “resist and release” for Alternative Bay Construction Method Cracking Control of Super Long Mass Concrete, Beijing: China Architecture & Building Press.

Xu R., 2012, Stepping into “Wang Tiemeng Method” & Emended Text of the Control of Cracking in Engineering Structure. Beijing: China Architecture & Building Press.

Xu R., Xu X., 2010, Control of Cracking in Engineering Structure—Examples of “Wang Tiemeng Method”. Beijing: China Architecture & Building Press.