Thermal changes of the environment and their influence on reinforced concrete structures

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Abstract. The thermal expansion of concrete elements concerns both monolithic and prefabricated structures. Inappropriate design of dilation segments may cause minor but even larger failures. Critical environment factors are temperature-changing operations, such as unheated underground garages, where temperature fluctuations may occur depending on the exterior conditions. This paper numerically and experimentally analyses the thermal deformation of selected girders in the underground garages and the consequent structure failures, their causes, possible prevention and appropriate remediation.

1. Introduction
Every structure bears a load that is designed for. Temperature load is one of the loads that act more or less on every structure. This load results from temperature expansion [1]. The phenomenon of thermal expansion is essential when designing huge or long structures as bridges, halls, frames, pipelines etc. [2], [3], [4], [5]. Thermal expansion is a material property and it is unique to each material [6]. It is common to combine materials with similar thermal expansion because of minimization of unfavorable stress states caused by temperature changes.

Similar thermal expansion coefficients α [1/°K] of steel (12 * 10⁻⁶ [1/°K]) and concrete (10 * 10⁻⁶ [1/°K]) allow using these two materials as a composite material called reinforced concrete. The reinforced concrete is one of the most frequently used materials for building structures. When designing these structures, it is necessary to consider thermal expansion which can be prevented by dilatation or reinforcement of the structure [7], [8], [9]. Otherwise, it may cause minor but even larger failures.

Temperature fluctuation is very often present open and unheated garage areas, for example shopping mall underground garages or garage of IT4Innovations national supercomputing center of Ostrava [10], [11].

Failures from the temperature change are almost perpendicular to the direction of failure source (thermal expansion). It is advisable to control the size of the cracks changing with temperature in order to determine the cracks caused by thermal expansion. This paper analyzes one yearlong monitoring of the creation and development of the cracks on shopping mall structure.

2. Structure and diagnostic methods
Cracks caused by thermal expansion were long-term monitored on reinforced concrete frame building. The main supporting structure is built out of prefabricated reinforced concrete members. The building
is supported by reinforcement concrete piles. Prefabricated RC girders transfer the load from the floor to the prefabricated RC columns underneath it.

It is the two-story multifunctional centre of polygonal ground plan located in the Czech Republic. The total area is approximately 160 x 145 m, the span between RC columns; 8 x 8 m in 1st Basement and 16 x 16 m in Ground floor. The girders are mounted on the column heads every 8 m. There are prestressed reinforced concrete panels lied down on the girders. The structure was designed in 2013 and put into operation in 2014.

![Figure 1. Ground plan of 1st basement with sensor location marked](image)

String tension sensors TSR/5.5 were attached to the columns holding up thermally stressed girders. Monitored columns can be seen in Figure 1. The sensors were recording cracks movements in the columns. The recording was carried out regularly by reading measures from the data logger. Temperature influences the girders volume changes, therefore the temperature was recorded as well.

![Figure 2. String tension sensor TSR/5,5](image)

String tension sensor TSR/5.5 contains a steel string tensioned between 2 fastening blocks on each end. The string is protected by steel tube which can move freely in fastening blocks. The waterproof electromagnetic coil is fixed in the middle of the length of the string tension sensor. The active length of the string is 139 mm. String frequency is approximately 1000 Hz when unstressed. String stress and frequency change due to deformation of the structure.
3. Thermal expansion of reinforced concrete

Thermal expansion is one of the basics mechanical properties of all materials including material as reinforced concrete for construction of structures. Thermal expansion is a habit of material to change length (volume) of the material as a response to temperature change. Almost every substance expands during heating that means molecules moving faster and its equilibrium positions are further apart.

3.1. Theoretical solution

Application of thermal expansion to the particular reinforced concrete frame formed by girders (simple beam) and columns give us a local requirement for dilatation of each girder [12], [13], [14], [15]. For the application of theoretical principles for a change of length depending on temperature by using the formula

$$\Delta l = \alpha \cdot l \Delta T$$

(1)

where $\Delta l$ is a change of the bar length, $\alpha$ is a coefficient of thermal expansion, $l$ is an initial length and $\Delta T$ is a change of temperature, we can get an extension of the element (length is 8 [m] and temperature change is 1 [°C]) about $8 \times 10^{-5}$ [m]. We can get roughly a change of tension/compression stress about 0.341 [MPa] on the C35/45 concrete member fixed at both ends and girder temperature change equals to 1 [°C] by the formula

$$\sigma = E \frac{\Delta l}{l}$$

(2)

By theoretical principle the strength of the concrete element equals to 1.47 MPa, the stress will reach the strength of unreinforced concrete when temperature change is 4.31 °C.

Boundary conditions are crucial in this case. According to static scheme and considerations of civil engineers, the girder is simply supported beam with sliding supports secured by steel stud connector.

![Girder support](image)

Figure 3. Girder support

It is very hard to implement these boundary conditions in practice. In this particular case, the simplified static scheme can be used as shown in Figure 4.
Figure 4. Simplified static scheme a) theoretical b) real

Figure 4a shows assumed static scheme and Figure 4b) real behavior of the structure. Movements of the outer ends of the girders are restrained due to heavy load by upper structures that’s why dilatation movements are realized only above the center column where the normal force is much smaller. The dilatation is limited by stud connectors (see Figure 3), if the maximum displacement of dilatation is reached, the static scheme will change to pinned girder and unfavorable tensile stress will occur in concrete due to thermal extension (change of temperature).

Figure 5. Monitored column failures of the shopping mall caused by thermal expansion of girders

The static scheme has been changed and the tensile strength of column was reached, therefore cracks occurred in concrete. Diagnostics of the structure showed that the crack occurred at the location of the steel stud connectors which reached their maximum displacement dilatation (see Figure 5). Diagnostics showed also that the number of column head stirrups is insufficient for transporting forces from girder thermal changes [16].
3.2. Experimental solution

The crack size change which responded mainly to the changes of the thermal longitudinal expansion of the concrete element was monitored during the diagnostics. The structure had been shrunk and crept during diagnostic, only deformations from the thermal expansion were monitored. Monitoring of the structure lasted one year so every season of the year could be monitored together with temperature changes. The temperature was one of the main monitored parameters of diagnostic and it fluctuated between 3 °C and 23 °C.

![Figure 6. Record of temperatures](image1)

Record of temperatures during a year can be seen in Figure 6. This is the temperature of the interior of the unheated garage area. The temperature was always measured on the structure close to the sensor location. Open space area caused delaying of temperature changes including reduction of outside environment temperature. The temperature has not reached a negative or extremely high value in this area. ΔT was approximately around 20 °C.

![Figure 7. Record of measured crack deformations](image2)
Change of the crack size was monitored by TSR/5.5 string tension sensor always on the left and the right side, so it was possible to see any asymmetry which would mean that the rotation in horizontal plane occurred. Figure 7 shows changing of the crack size which is slightly parallel to the temperatures shown in Figure 6.

3.3. Comparison
Based on measured temperatures and known parameters of girder it is possible to obtain a graphic representation of the girder theoretical behaviour according to the application of thermal expansion shown in chapter 3.1. The result is shown in Figure 8. This figure shows a curve variation of girder extension according to the temperature [17], [18], [19], [20].

![Figure 8. Graphical record of the theoretical crack deformation](image)

Comparison between theoretical and measured values is shown in Figure 9. It is obvious that the values are similar for both approaches.

![Figure 9. Graphical record of the experimental and theoretical crack deformation](image)
Difference between theoretically and experimentally obtained values is primarily caused by boundary conditions of girder supports [21], [22].

![Figure 10](image.jpg)

Figure 10. Dependence of crack deformation on temperature from experimental and theoretical values

Figure 10 shows that the values obtained from the theoretical calculation are comparable with the values obtained from the left sensor. Values from the right sensor deviate from the theoretical calculation, especially at low temperatures. That means there is horizontal asymmetry caused by boundary conditions at girder supports.

According to the crack size changes which corresponds to displacements of a beam fixed at one end and pinned at another end, the assumption of the static scheme from the Figure 4b) is confirmed. Due to change of static scheme, unequal distribution of tension stress caused by girder thermal shrinkage occurs, therefore the phenomena of thermal shrinkage works on the side of lower stiffness only.

4. Conclusion

It is necessary to consider the physical properties of materials during design. Specifically is thermal expansion associated with material and especially with temperature change, therefore it can cause large failures of the structures. Thermal expansion in structures can be prevented by dilatation or reinforcement of the structure.

Sometimes only dilatation itself does not have to be sufficient when boundary conditions change as described in this article. Restoration of this particular case is possible for example with classics steel bandage replacing the absence of reinforcement in the tensile direction [23], [24]. It is appropriate to apply this steel bandage during the highest shrinkage of the girder. Otherwise, it could cause failures of others structure elements as a result of redistribution of the girder thermal expansion effects.

For a designer, it is necessary to consider the real structure behavior including thermal expansion of materials and its possible consequences. It is fundamental to prevent potential failures in order to avoid damage or collapse of the structure.

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