Experimental Verification of Reinforced Concrete Member under Cyclic Loading

Alena Čavojcová*, Martin Moravčík, František Bahleda, Jozef Jošt

a University of Žilina, Faculty of Civil Engineering, Department of Structures and Bridges, Univerzitná 8215/1, 010 26 Žilina
b Research Centre of University of Žilina, Univerzitná 8215/1, 010 26 Žilina

Abstract

Fatigue failure is characterized by a fracture in a local area of a structure which is subjected to varying cyclic loading. This loading can be caused by traffic, wind, ocean waves or likewise. The fatigue life of a reinforced concrete structure depends as much on the stress levels as on the stress range and the number of loading cycles and their importance is related to which material that is considered. Concrete structures are verified for the fatigue resistance only if it is recommended by the European Standard STN EN 1992-1-1[1]. The purpose of this paper is to compare the damaged equivalent stress range methods for fatigue assessment available in above mentioned standard to the experimental verifications.

Keywords: concrete structures; fatigue; cyclic loading; experimental study

1. Introduction

Fatigue is generally effect of degradation, which reduces the structural service life. The service life of reinforced concrete structure directly depends on the stress level, stress range and number of the loading cycles during the cyclic loading.

The structures under static loading have been generally verified according to the current European standards for the standard shear, bending resistance or their combination or another one that depends on the loading effects character. Concrete structures under dominant cyclic loading effects have to be verified from the fatigue resistance point of view. The fatigue assessment approach according to the STN EN 1992-1-1[1] consists of the verification procedures for the concrete and reinforcement separately. For the concrete the damage equivalent compression stresses have been verified using the boundary stresses $\sigma_{c,min}$ and $\sigma_{c,max}$ in concrete. The damage equivalent stress range method the real operational loading is condensed to a single amplitude at $N^*$ cycles. The damage equivalent stress in reinforcement is $\Delta\sigma_{S,Eq}(N^*)$. The comparative value of the steel fatigue resistance at N cycles is $\Delta\sigma_{R,sk}(N^*)$.

* Corresponding author. Tel.: +421 41 5135656.
E-mail address: alena.cavojcova@fstav.uniza.sk
practically derived from the appropriate S-N curve, which the standard offer, or the curve which can be obtained from the experimental measurements.

The main goal of this paper has been to verify the standard approach and compare to our experimental results from the number of cyclic loading during the element service life. For that purpose we chose the reinforced concrete T-beam, which was designed from the bending moment and shear reliability condition satisfied from the static character of the load effect but did not satisfy for the cyclic loading condition.

2. Experimental program description

Five specimens of T-beam were made-up from the concrete class of C35/45 with reinforcement 3 Ø 12 mm, steel B500 B. All tested beams are designed as simple supported elements. Some details of the T-beam are shown in (Fig. 1 a, b) and (Fig. 2 a, b).

![Fig. 1](image1.png) ![Fig. 2](image2.png)

Two beams were tested under the 4-point bending to this time. One beam as a comparative element under static load and other one for the cyclic load. Following parameters have been recorded:

- Beam deflection – three measurement points – in the middle of the span and in the quarters, using the potentiometric sensors,
- Propagation, development and width of the cracks (bending and shear) along the span,
- Strains of the concrete – on the top of the flange and reinforcement – one steel rod using the strain gauges in the middle of the span,
- The support area deformation control – at two measurement points.

The next 3 beams will be tested in summer 2014. These beams will be strengthened by the system of NSM (near surface mounted). There is planning of the strengthening system using the strips MBRACE 20/1.4 mm. One beam will be tested under static loading and two ones will be tested by dynamic loading. That research works will be focused to the possibility how to increase the actual fatigue resistance of concrete members using the bond materials strip - adhesive - concrete.
3. Theoretical design proposes designed concrete beam

T-beam was design according to [1] that satisfy the reliability condition from the static load effect point of view, relation (1)

$$M_{Rd} \geq M_{Ed}$$  \hspace{1cm} (1)

For the fatigue resistance, the standard [1] recommends the simplified damage equivalent stress range method. There can be used the simplified relation (2) for the concrete under compression with boundary stresses $\sigma_{c,\text{max}}$ and $\sigma_{c,\text{min}}$ using the reduced fatigue concrete strength, $f_{cd,\text{fat}}$. Our designed beam satisfied using that condition. Shear resistance of the beam was just sufficient. The steel reinforcement was designed so that reinforcement have been underestimated due to the fatigue loading that means as insufficient fatigue resistance according to the condition (3).

$$\frac{\sigma_{c,\text{max}}}{f_{cd,\text{fat}}} \leq 0.5 + 0.45 \frac{\sigma_{c,\text{min}}}{f_{cd,\text{fat}}} \leq 0.9 \hspace{1cm} (2)$$

$$\gamma_{F,\text{fat}} \Delta \sigma_{S,\text{eqp}} (N^*) \leq \frac{\Delta \sigma_{R,\text{sk}} (N^*)}{\gamma_{S,\text{fat}}} \hspace{1cm} (3)$$

The graph (Fig. 3) shows the fatigue resistance and number of cycles for design loading according to the standard S-N curve for the reinforcement steel. Design values for our stress range was $\Delta \sigma_s = 200$ MPa, with maximum stress value $\sigma_{s,\text{max}} = 325$ MPa and minimum stress value $\sigma_{s,\text{min}} = 125$ MPa.

![Graph showing fatigue resistance and number of cycles](image)

Fig. 3. Equivalent stress and fatigue resistance of the steel rod.

4. Experimental results

The first beam, as a comparative element, was tested under monotonic static load with increasing steps. The first visible crack has been occurred near the middle of the span at the value of load force $F_{cr} = 23$ kN. Other cracks on the tested beam were recorded symmetrically along the span. Failure of the beam has occurred at the level of load force $F_u = 110$ kN. Maximal crack was width 1.2 mm for static loading.
Second beam was tested under cyclic loading (Fig. 4). At first the beam was loaded on the starting load level value $F_o = 45$ kN that means the average of the stress range and then it started under cyclic loading. The range of cyclic loading was around 45 kN, which represents 40 % from yield strength of steel. This value approximately represents the operating stress in the concrete bridges with middle length span. The upper load limit was 65 kN and down limit was 25 kN. The value of down limit has been chosen on the level $1.10 \times F_{cr}$. Loading frequency was 2.0 Hz that is the typical service frequency on the concrete bridges. The graph (Fig. 5) shows the relation between the tension stress and number of cycles on observed steel rod. It can be seen that the significant stress is increasing in the last 70 000 cycles. Crack in reinforcement was observed in 530 000 cycles level. The failure mode of the beam was rupture one of the steel rod, see the (Fig. 6) at the 545 000 cycles. That corresponds to the theoretical value.
The graph (Fig. 7) shows the compression stress of the concrete on the top of T-beam flange. In Fig. 7 one can see very slight increasing of the concrete stress, as was assumed. This behaviour in the compression zone complies with the theoretical calculation.

![Graph showing compression stress and number of cycles in the concrete.](image1)

**Fig. 7.** Relation of the compression stress and number of cycles in the concrete.

The graph (Fig. 8) shows the beam deformation in the middle of the span. Deformation was again increased only slightly, small growth can be seen from the level of 50,000 cycles. All cracks have been observed during experimental testing of the beam (Fig. 9 (a)). Similar effect of the bending stiffness decreasing due to the crack development we have recorded at the level around 50,000 cycles, see the (Fig. 10). The crack pattern illustrates Fig. 9(a).

![Graph showing beam deformation due to number of cycles.](image2)

**Fig. 8.** Deformation development due to the number of cycles.

![Images showing final crack pattern and dominant crack.](image3)

**Fig. 9.** (a) Final crack pattern of the beam; (b) Dominant crack in the bottom of the T–Beam.
The graph (Fig. 10) shows the main bending crack width development in the middle of the span due to the number of cycles.

![Graph of crack width development](image)

Fig. 10. Relation of the main crack width.

Crack pattern were controlled from the crack width point of view. In the bending zone in the areas through the steel beam where the load is distributed to the beam, many cracks were concentrated, symmetrically distributed. Crack No. 1 had width 0.4 mm in the level of 530 000 cycles. Failure of the beam by the reinforcement rupture has occurred at the same place as the crack No. 1 is located, in 545 000 cycles. Width of the crack No. 1 was around 4.0 mm (Fig. 9 (b); 10).

5. Conclusion

Assumed fatigue behaviour of the concrete T-beam was confirmed. Damage equivalent stress range method gives satisfactory results to the fatigue behaviour prediction. Supposed failure mode as the steel rod rupture of our tested T-beam was recorded and confirmed. Critical number of cycles corresponds well to the theoretical prediction, see Fig. 3. In the next research we would like to focus on the fatigue resistance increasing, based on the adhesive systems where the NSM method belongs.

Acknowledgement

This contribution is the result of the research supported by VEGA 1/0517/12, VEGA 2/0143/12, APVV-0736-12 and this research is supported by European regional development fund and Slovak state budget by the project Research centre of University of Žilina, ITMS 26220220183.

References

[1] STN EN 1992-1-1 Eurocode 2: Design of concrete structure, Part 1-1: General rules and rules of building.
[2] STN EN 1992-2 Eurocode 2: Design of concrete structures, Concrete bridges, Design and detailing rules.
[3] P. Koteš, P. Kotula, F. Bahleda, M. Brodhan: Experimental investigation and numerical modelling of concrete structures with GFRP members, 6-th CCC Congress Marianske Lazne 2010, pp. 149-154.
[4] W. Dermanowski: Fatigue life of reinforced concrete beams under bending strengthened with composite materials, in: Archives of civil and mechanical engineering, 2006, pp 33-47.
[5] K. Gajdošová: Stress and Crack width control according to EN 1992, International workshop: Proceedings, 2012, pp 199-202.
[6] J. Halvönik, V. Borzovič, J. Dohnák: Experience with design of prestressed concrete bridges according to Eurocode, in: Design of concrete structures using EN 1992-1-1: First International Workshop, 2010, pp 61-71.