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COMPOSITE TIMBER-CONCRETE STRUCTURES UNDER HIGH-CYCLE FATIGUE LOADING

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Summary: *Composite timber-concrete beams are innovative structural elements that are the subject of research in recent decades due to their attractive mechanical properties and possible solutions of various problems in rehabilitation and reconstruction of timber buildings. They can be met in the new constructions of commercial and residential buildings, but increasingly, in the construction of timber bridges of longer spans. The behaviour of composite timber-concrete beam under static, short-term or long-term loading is subjected to ongoing research in order to confirm, extend or improve the existing knowledge and numerical models. When it comes to dynamic load, it can be said that these efforts are small, especially when it comes to high-cycle load, so characteristic for bridges. This paper provides information on the parameters that define high-cycle fatigue loading, the parameters that describe the possible behaviour of composite timber-concrete under high-cycle fatigue loads. Certain numerical and analytical models of steel, concrete and fasteners, separately exposed to high-cycle fatigue load, will be presented in this paper, too.*

Keywords: *Composite timber-concrete beam, high-cycle fatigue load.*

1. INTRODUCTION

Timber-concrete composite structure is known as a structure where two different sections (made of timber and concrete) are connected to a composite cross-section with special connection systems. Connecting systems accept shear forces of interface and provide simultaneous acting of different materials in composite system, under loading. As connecting systems may be used:

- screws, bolts, nail plates or glued threaded rods,
- special components made of steel such as s steel lattice glued to timber, and steel plate glued to timber,

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- a shear key-anchor detail, notched shear key with a steel dowel tension anchor.

From a structural point of view, the compound of two partial cross sections of timber and concrete causes different stress state along both cross-sections. Beams, as timber-concrete composite structures, combine in their sections timber in the tension zone and concrete in the compression zone. Between the partial cross sections the connecting system is arranged to provide a compound of the partial cross sections and to transfer the shear forces occurring between timber and concrete. Figure 1 illustrates the composite simple beam behaviour under bending loading in dependence on the degree of composite action.

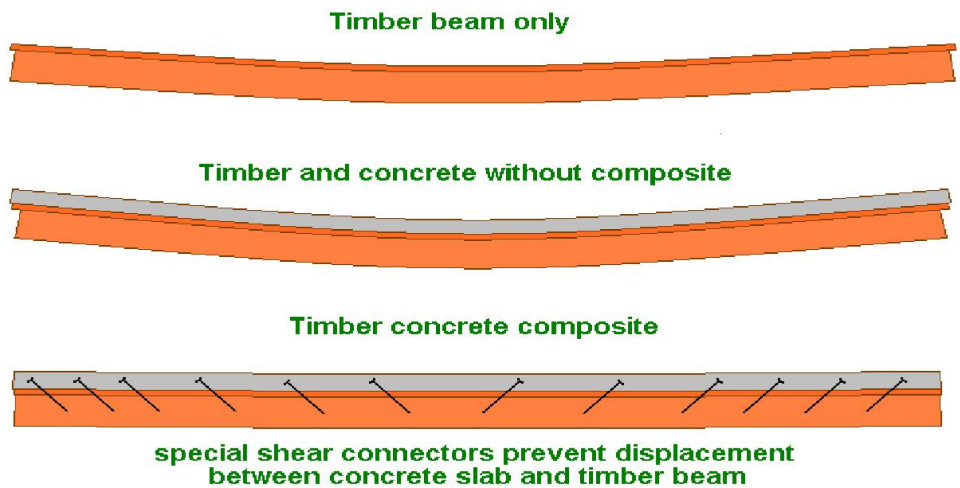

Figure 1. Behaviour of composite timber-concrete beam

Timber-concrete composite structure has important structural applications, including the refurbishment of existing timber floors, the introduction of new floor types, and as a deck system for timber bridges. Timber-concrete composite systems have a positive influence on sound insulation and on fire safety. When used for a bridge deck, the method protects the timber from direct sun and rain thanks to the concrete slab. By using of composite timber-concrete systems we can build our structure faster, with less concrete formwork and less stabilization elements, and we have reduced foundations because of less structural weight, better behaviour under an earthquake loading.

2. BASICS OF HIGH CYCLE FATIGUE LOADING, THE *S-N* CURVE, MATERIAL MODELS

According to *ASTM International* (American Society for Testing and Materials), fatigue is "the process of progressive localized permanent structural change occurring in a

material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.“
General categories and approaching methods include:

High-cycle fatigue, associated with low loads and long life (>10^3 cycles), is generally analyzed with a "stress-life" method (the *S-N* curve), which predicts the number of cycles sustained before failure, or with a "total-life" method (endurance limit), which puts a cap stress that allows the material to have infinite life (>10^6 cycles).

Low-cycle fatigue, associated with higher loads (plastic deformation occurs) and shorter life (<10^3 cycles), is commonly used methods called "strain-life" to analyze or predict the fatigue life.
The *S-N* curve, (Stress Life Method) is the basic method presenting fatigue failure in high cycles ($N > 10^5$) which implies the stress level is relatively low and the deformation is in elastic range.

The *S-N* curve for a specific material is the curve of nominal stress *S* (*y* axis) against the number of cycles to failure *N* (*x* axis). A log scale is almost always used for *N*. The stress is usually nominal stress and is no adjustment for stress concentration. The curve is usually obtained one by reversed bending experiments with zero mean stress.
The *S-N* curve of 1045 steel and 2014-T6 aluminium alloy is shown on the Figure 2 to represent two typical *S-N* curves of metal materials. On the Figure 3 is shown S-N curve for a timber. The *S-N* curve is used to predict the number of cycles sustained under certain stress before failure. The curve gives to designers a quick reference of the allowable stress level for an intended service life.

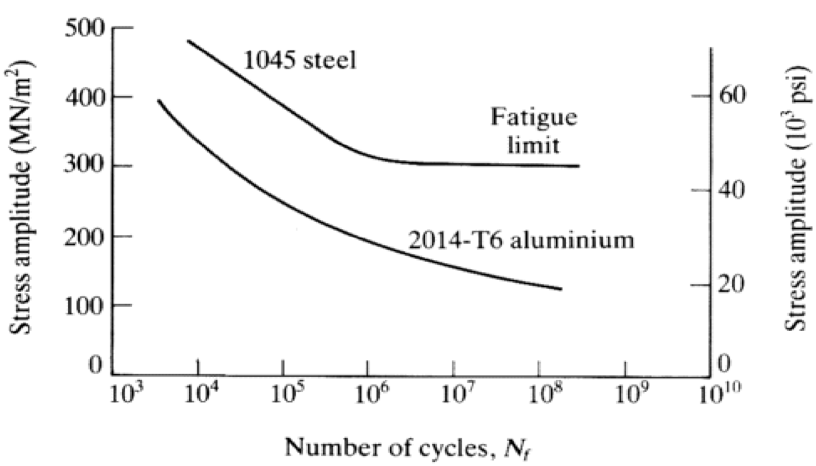

Figure 2. The S-N curve of 1045 steel and 2014-T6 aluminium

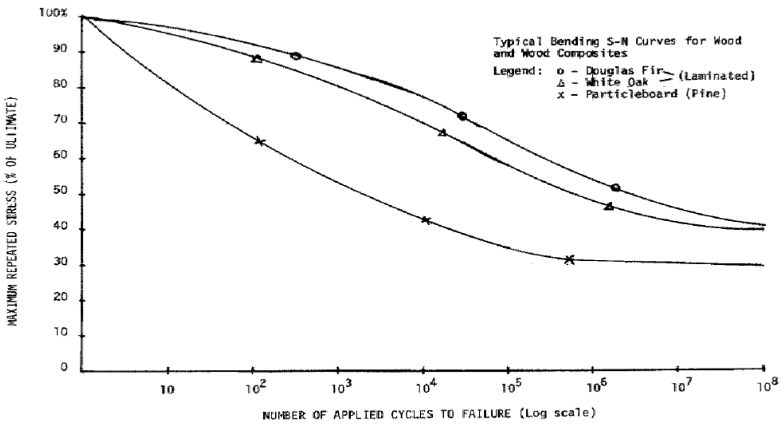

Figure 3. The S-N curve for a timber

3. FATIGUE MODEL FOR CONCRETE

Classical observations on fatigue of concrete focus on the determination of a relationship beetwen the applied stress level and the fatigue life time, resulting in the well known S-N curves. In experimental investigations, Holmen (1979) observed S-shaped evolution curves of the maximum and minimum fatigue strains. Accordingly, the entire fatigue life can be subdivided into three periods with different deformation mechanisms: initiation of micro cracks, their stable growth and finally localisation to a macro crack.

For concrete in the compression region a yield/damage criterion of Drucker-Prager type is applied:

$$\phi(\sigma,\alpha) = \frac{1}{\frac{1}{\sqrt{3}} - \mu}\left[\mu I_1 + \sqrt{J_2}\right] - \alpha_c(q_c) \tag{1}$$

The final constitutive relation results in:

$$\sigma = \left[D^0 + D^{da,c} + D^{fat,da}\right]^{-1} : \left[\varepsilon - \varepsilon^{pl} - \varepsilon^{cr} - \varepsilon^{fat,pl}\right] \tag{2}$$

4. FATIGUE MODEL FOR A REINFORCING STEEL

The basic concept for the fatigue damage modelling of reinforcing steel is adopted from Petryna (2002) and Pfanner (2003). The basic variable to determine fatigue damage is the related number of load cycles n, in analogy to the procedure for concrete. For the evolution of fatigue damage, an exponential law, according to Peerlings (1999), is applied:

$$d_s = -\frac{1}{\vartheta_s}\ln\left[1-\left(1-e^{-\vartheta_s}\right)n\right]d_s^{fail} \quad (3)$$

The stress is connected to the damage variable d_s with the constitutive law

$$\sigma_{\max} = E\left(1-d_s\left(\sigma_{\max}\right)\right)\varepsilon \quad (4)$$

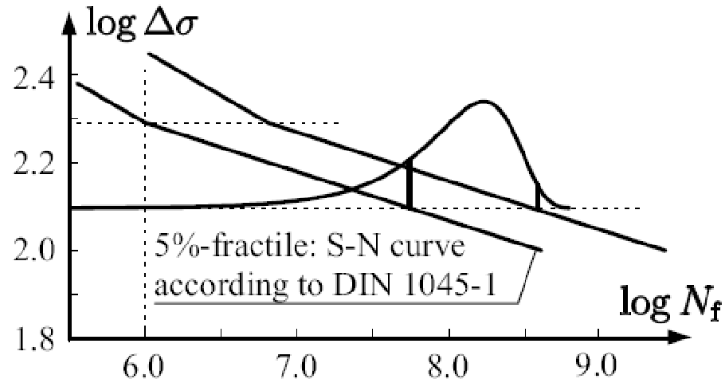

Figure 4. Fatigue model of reinforcing steel

5. FATIGUE MODEL FOR A TIMBER

The following timber failure models in literature are presented:

- damage accumulation laws,
- polymer debonding,
- energy based models ,
- damaged viscoelastic material model,
- number of cycles criterion.

In the number of cycles criterion, W¨ohler curves, or S-N diagrams, describe fatigue resistance by a critical number of load cycles, ***N***, leading to failure at a given stress level, (***SL***). It can be described by a relation:

$$\log(N) = A + B \cdot \log(SL), \quad (5)$$

A** and **B the coefficients depend on the factor ***R***, $R = \sigma_{min}/\sigma_{max}$, where σ_{min} and σ_{max} are the min and max stress level in a cycle. Steady state crack growth due to stress variations can be given according to linear elastic fracture mechanics. Relation between crack growth rate and the stress intensity factor in the following form (Paris law) is given:

$$da/dn = C\,(\Delta K)^m, \quad (6)$$

where ***a*** is crack length, ***n*** is number of cycles, ***ΔK*** is the variation of the stress intensity factor, ***C, m*** constants. If **ΔK** is given as function of stress variation and number of cycles as a continuous variable, an integration of (6) will give the number of cycles corresponding to final crack length.

$$N = C' (\Delta\sigma)^m. \quad (7)$$

6. FATIGUE DESIGN CODE RULES

In the bridge part of the Eurocode, (EC5-2 1997), an informative annex gives guidelines for a simplified fatigue verification method. The method considers only number of cycles. According to the method it should be verified that:

$$\Delta\sigma \leq f_{fat,d}, \quad (8)$$

where the stress range of the fatigue loading is determined as $\Delta\sigma = \sigma_{max} - \sigma_{min}$.
The fatigue strength $f_{fat,d}$ is determined in dependency of the number of load cycles according to:

$$f_{fat,d} = k_{fat} f_k / \gamma_{M,fat} \quad (9)$$

In DIN 1074:2006, Section C, simplified proof is based on a high cycle fatigue loading with constant amplitude A fatigue analysis is always required when the ratio is greater than in DIN 1074:2006, Table C.1 specified.

Formula	Symbol	definition
$k = \dfrac{\lvert\sigma_{d,\max} - \sigma_{d,\min}\rvert}{\dfrac{f_k}{\gamma_{M,fat}}}$	$\sigma_{d,\max}$	maximum stress level in the cycle due to fatigue action
	$\sigma_{d,\min}$	minimum stress level in the cycle due to fatigue action
	f_k	characteristic strength
	$\gamma_{M,fat}$	partial safety factor for materials for the fatigue analysis M, fat = 1.0

Table 1. Calculation of the ratio

7. CONCLUSION

This short paper presents the basic parts of a very complex mechanical behavior of timber-concrete composites under high cycle fatique load. Appropriate analysis, analytical and numerical models, material laws will be presented in other works.

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СПРЕГНУТЕ КОНСТРУКЦИЈЕ ТИПА ДРВО-БЕТОН ИЗЛОЖЕНЕ ВИСОКОЦИКЛИЧНОМ ЗАМОРНОМ ОПТЕРЕЋЕЊУ

Резиме: *Греде добијене спрезањем дрвета и бетона представљају иновативне конструкцијске елементе који су последњих деценија предмет истраживања због њихових атрактивних механичких својстава и могућности решења различитих проблема приликом санација и реконструкција објеката грађених у дрвету. Срећу се у новим конструкцијама пословних и стамбених објеката, али све више и у конструкцијама дрвених мостова већих распона. Понашање спрегнутих греда типа дрво-бетон под статичким, краткотрајним или дуготрајним оптерећењем, предмет је сталног истраживања, у циљу потврђивања, проширења, побољшања постојећих сазнања и рачунских модела. Када је у питању динамичко оптерећење, може се рећи да су та настојања скромна, посебно када је у питању високоциклично заморно оптерећење, тако карактеристично за мостове. Овај рад даје информације о параметрима који дефинишу високоциклично заморно оптерећење, у општем смислу и о параметрима који описују могућа понашања спрегнутих конструкција типа дрво-бетон изложених високоцикличном заморном оптерећењу. Одређени нумерички и аналитички модели челика, бетона и спојних средстава, сепаратно изложених високоцикличном заморном оптерећењу биће представљени у овом раду, такође.*

Кључне речи: *Спрегнуте конструкције типа дрво-бетон, високоциклично заморно оптерећење.*