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DESIGN OF FIBRE-POLYMER COMPOSITE STRUCTURES – EUROPEAN TECHNICAL SPECIFICATION: FATIGUE AND DETAILING

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Abstract: *The paper gives an overview of the clauses about fatigue and detailing of the new European Technical Specification 'Design of Fibre-Polymer Composite Structures'. A fatigue verification criterion and information about fatigue action models are provided first. The fatigue verification format, including the composition of a single partial factor for the fatigue resistance, are then explained. Subsequently, the specifications about fatigue testing, with a focus on bridge deck applications, are summarized. Finally, the recommendations for the detailing of laminates, profiles, sandwich panels, bolted and bonded joints, and bridge details, are addressed.*

Keywords: Fibre-polymer composites; European Technical Specification; Fatigue; Detailing

1. Introduction

Fibre-polymer composite load-bearing structures are sensitive to fatigue damage, mainly due to (i) the brittleness and anisotropic-layered fibre architecture of composite materials, and (ii) the fact that variable loads normally are high compared to permanent loads, in particular traffic loads in bridge construction.

A composite structural member or joint in bridge and other civil engineering structures can exhibit several different and complex fatigue failure modes. Failure rarely occurs in the basic member components (e.g., in laminates or sandwich cores), but in most cases in component connections and interfaces, i.e., at singularities with stress concentrations in different directions. Rather than basic component fatigue testing (of laminates or cores of sandwich panels), assemblies of components would thus need to be tested (e.g., a web-flange junction). The test set-up of such component assemblies is however complicated, the number of tests required to cover all the possible cases is rather large, and the interpretation of the results is difficult. At these singularities, local stresses normally cannot be obtained easily and reliably. Determining partial factors of fatigue resistance models for such cases seems impossible moreover due to missing data [2].

The fatigue verification method implemented in Clause 10 of the CEN Technical Specification (TS) '*Design of Fibre-Polymer Composite Structures*' [1] is thus performed on the level of the members and their joints, and their internal forces and moments, and not on the level of components and their stresses. This approach also takes into account the effects of geometrical and material imperfections and size effects on the fatigue behaviour.

Stress concentrations can also be minimized by an appropriate detailing of geometrical changes or changes of materials in members, or of member joints and their connections. Recommendations for detailing are thus provided in Clause 11 of the TS and in the informative Annex E for bridge details.

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2. Fatigue verification criterion and action models

A fatigue verification criterion was established as a 95% lower confidence bound of numerous fatigue test results of various composite materials documented in literature [2]. The criterion allows to check whether a fatigue verification is required for a structural member or joint. A verification is required if the following condition is fulfilled:

$$E_{\mathrm{d}}\left(\gamma_{\mathrm{Ff}}\cdot Q_{\mathrm{fat}}\right)/R_{\mathrm{d}} > 1{,}6 - 0{,}18\cdot\log N \tag{1}$$

where

$E_{\mathrm{d}}\left(\gamma_{\mathrm{Ff}}\cdot Q_{\mathrm{fat}}\right)$	is the design value of an action effect in the structural member or joint (an internal force and/or moment), caused by the fatigue action model;
γ_{Ff}	is the partial factor for the fatigue action (according to EN 1990, normally =1.0);
Q_{fat}	is the relevant constant amplitude fatigue action (see below);
R_{d}	is the design value of the corresponding static resistance of the member or joint;
N	is the number of cycles of the fatigue action, i.e. the number of axle loads.

Concerning the above-mentioned action effects, in the case of bridges, a still unsolved problem is that a fatigue action model for traffic loads tailored to composite bridge structures does not yet exist. The current action (or load) models, FLM1-3 of EN 1991-2, which are mainly composed of different truck axle load configurations, were calibrated for steel and concrete bridges, and FLM4 represents a variable amplitude (VA) loading. Applying a VA fatigue verification was however considered to not be reliable and applicable for composites in the framework of this TS since the associated use of the linear Palmgren-Miner's damage rule, in many cases, may significantly over- or underestimate the fatigue life [2, 3]. The fatigue action model for composites should thus be selected and agreed case by case by the relevant parties, until a composite-tailored model will be available. The model should take into account the mean stress level (or the *R*-ratio) exhibited by the actual actions, to which the fatigue behaviour of composites in sensitive [2, 4].

3. Fatigue verification

As introduced above, the fatigue verification implemented in the TS is performed at the structural member or joint level and is based on the design value of an internal force or moment, as follows:

$$E_{\mathrm{d}}\left(\gamma_{\mathrm{Ff}}\cdot Q_{\mathrm{fat}}\right)\leq\frac{\eta_{\mathrm{c}}}{\gamma_{\mathrm{Mf}}}\cdot R_{\mathrm{f,\,k}} \tag{2}$$

where

$R_{\mathrm{f,\,k}}$	is the characteristic value of the fatigue resistance of the member or joint, which should be obtained from member or joint testing, at constant amplitude;
γ_{Mf}	is the partial factor for the fatigue resistance, to be selected according to Table 1;
η_{c}	is an environmental conversion factor (see TS, Clause 4 and [2]).

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The characteristic value of the fatigue resistance is obtained from a constant amplitude action model since a variable amplitude verification is not considered to be applicable, as explained above.

A single partial factor for the fatigue resistance is applied, γ_{Mf}, which accounts for both the uncertainty in the resistance model and unfavourable deviations of the relevant material or product properties from their characteristic values. As shown in Table 1, the factor depends on (i) the type of inspection and maintenance and accessibility of the critical details, and (ii) the consequences of failure, i.e., whether a member or joint is fail-safe or not. In fail-safe structural members or joints, local failure of the member or joint should not result in failure of the structure or critical parts thereof. In non-fail-safe members or joints, local failure of the member or joint could lead to failure of the structure or critical parts thereof.

Table 1: Partial factors for fatigue resistance, γ_{Mf}

Inspection and access	Fail-safe	Non-fail-safe
Member or joint subjected to periodic inspection and maintenance, detail accessible	1,5	2,0
Member or joint subjected to periodic inspection and maintenance, limited accessibility	2,0	2,5
Member or joint not subjected to periodic inspection and maintenance	2,5	3,0

The format of Table 1 was adopted from Table 4.19 in EUROCOMP [5], since its composition is in line with prEN 1990, 8.3.5.4(1), which specifies that the partial factor for the fatigue resistance should account for the consequence of fatigue failure and the ease of inspection and repair of fatigue-sensitive members. The values listed in Table 1 were also adopted from EUROCOMP, Table 4.19, although it was not possible to find their origin and thus directly validate them. Based on several plausibility checks, the values were however found to be plausible (details are given in [2]), but they require further verification in the future.

4. Fatigue testing

4.1 General

As indicated in the previous section, the characteristic value of the fatigue resistance should be obtained from testing on the member or joint level, normally under constant amplitude loading. The test should be conceived to reproduce the same design values of the action effects (internal forces and/or moments) as in the structural member under the fatigue action model. The applied fatigue test load should therefore be equal to the design value of the fatigue test load, divided by the conversion factor and multiplied by the partial factor for the fatigue resistance, according to Eq. (2). Furthermore, the fatigue test load should be adjusted, i.e., the maximum and minimum values selected, to represent the same mean stress level (or R-ratio) as in the structural member (see above). The selected test frequency should be low enough to not cause inadmissible heating effects.

Testing should be performed for two purposes, for general member qualification and case-by-case proof, in line with EN 1990, D3(1a) and D3(1e), respectively.

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4.2 Bridge decks and slab bridges

In the case of composite bridge decks (installed on main girders, normally made of steel) or composite slab bridges (without additional main girders), qualification testing should be applied only once for each new product or design. Additional proof testing may be performed for each new application of the product or design, to verify that the assumed properties are achieved on site and/or to validate project-specific adaptations of the product. Proof testing may be disregarded when agreed by the relevant parties.

Qualification testing to approve a product or design should include:

- at least three static tests to determine the characteristic value of the static resistance; the coefficient of variation of the static resistance should be lower than 0,10;
- a minimum number of fatigue tests, as specified in Table 2;
- after concluding the fatigue loading with the number of cycles specified in Table 2, on each specimen, a post-fatigue static test run to failure under the same conditions as the static tests.

Table 2: Required number of fatigue tests and fatigue cycles in qualification testing for bridges of 50 and 100 years of design service life

Traffic category [a]	Minimum number of fatigue tests	Number of fatigue cycles (x10^6)			
		50 years		100 years	
		Local traffic [a]	Long-distance traffic [a]	Local traffic [a]	Long-distance traffic [a]
1	3	10	15	15	50
2	3	2	5	5	10
3 and 4	2	2	2	2	2
[a] according to EN 1991-2					

The required number of cycles for qualification testing was derived from EN 1991-2, assuming, as explained in [2]:

- the four traffic categories and the corresponding N_{obs} (heavy vehicles), acc. to Table 4.5 of EN 1991-2;
- the three traffic types/mixes and five vehicle types and their percentages, acc. to Table 4.7 of EN 1991-2;
- global or local effects, the former caused by the whole vehicle, the latter caused by the individual wheels/axles;
- for local effects, using weighted axle averages from Table 4.7 of EN 1991-2, resulting in 2, 3, 4 axles (rounded values), for local, medium, long-distance traffic, respectively;
- a design service life of 50 or 100 years.

The qualification testing is considered to be successful if:

- the required number of cycles is completed without failure;
- the stiffness reduction is less than 5%, to prevent excessive micro-cracking;
- detectable damage, i.e., macro-cracks, debonding, delamination that could affect durability due to moisture ingress does not occur;

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- the result of the post-fatigue static test is within two standard deviations of the mean value of the static resistance achieved in the static tests.

Based on a successful qualification testing, the action effect derived from the characteristic fatigue test load (internal force and/or moment) represents the characteristic value of the fatigue resistance, $R_{f,k}$, in Eq. (2).

Although a VA fatigue verification is not considered in the TS due to the above-mentioned reasons, a VA test load can nevertheless be applied, and the procedure and criteria defined above for a successful qualification testing can be adopted to verify the fatigue resistance.

Further specifications are provided in the TS regarding the test loading device configuration and the consideration of the surfacing layer. In bridge decks, the tyre-deck contact area (i.e., its size and shape) and the contact pressure distribution in this area are complex and depend on several factors, i.e., the tyre geometry and inflation pressure, the surfacing stiffness, and configuration of the deck, i.e., the deck stiffness distribution below the tyre. For instance, the contact area and pressure distribution on the top flange of a cellular deck system and on the top face sheet of a sandwich deck are different due to the different deck component stiffnesses. Furthermore, in the cellular case, significant differences also exist depending on whether the load is applied on a stiff top flange-web joint or on the more flexible top flange between the flange-web joints; more details are given in [2].

Since the fatigue life of deck systems can be very sensitive to the contact area and pressure distribution, particularly in cellular systems where the top flange is subjected to local bending and shear, the loading device configuration applied in testing should simulate the actual contact area and pressure distribution as closely as possible.

Contact pressure measurements on cellular bridge deck systems demonstrated that the pressure decreases to zero at the edges and does not exhibit concentrations as is the case under a steel plate of a loading device [2]. The bending stiffness of a steel plate, as an element of the loading device, should thus not affect the contact pressure distribution, i.e., a softer pad should be placed between the steel plate and deck to prevent a load transfer only at the edges of the device through concentrated local pressure. Finite element analysis can be used to design the soft pad (i.e., its thickness and stiffness) between the steel plate and deck under the fatigue test load.

The consideration of the bridge deck surfacing is also important since it can have two positive effects, depending on the surfacing thickness and stiffness, i.e., (i) a load spreading which results in a larger loaded area on the composite deck's top face (below the surfacing) compared to the tyre-surfacing contact area, and thus a more widely distributed pressure, and (ii) a strain reduction in the composite top laminate or flange caused by the flexural composite action between surfacing and composite top laminate or flange [2].

These positive effects depend however on the surfacing temperature and loading rate. An increasing surfacing temperature, i.e., a possible softening of the surfacing polymer components, can reduce these effects, while a higher loading rate, resulting in a corresponding surfacing stiffening, can increase the effects. If the surfacing layer has a significant stiffness, e.g., in the case of polymer concrete, the surfacing layer may be taken into account in the design and fatigue testing. If this applies, the effects of temperature and loading rate on the surfacing layer stiffness should however be considered.

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5. Detailing

The TS also provides recommendations for the detailing of member laminates, profiles, sandwich panels, bolted and bonded joints (in Clause 11), and generic examples of bridge details (in Annex E), such as bearings, expansion joints, parapets, and crash barrier fixations. The goals of these design recommendations are to ensure that stress concentrations are avoided or minimized and that effects of environmental conditions are reduced, e.g., by appropriate protection or dewatering systems. The reduction of stress concentrations also improves the fatigue resistance, see previous sections.

Concerning profiles, it is recommended to use closed sections since outstanding flanges are sensitive to damage, which can be easily caused by local impact. Furthermore, geometrical recommendations are provided for member laminates, such as sandwich panel face sheets, concerning thickness changes (tapering), and angles and overlap lengths of scarf, step-lap or single-strap connections; indications for sandwich core connections and core inserts are also provided.

For bolted joints, recommendations for nominal bolt diameters and bolt hole clearances, end edge distances for single- or multi-row bolted connections, and distances between centres of bolt holes are specified.

Adhesive connections should be designed symmetrical and with minimized eccentricities to reduce peeling stresses, to which the composite adherends normally are sensitive due to their layered fibre architecture. Tapering of the adherends and adhesive fillets can reduce stress peaks in lap-shear connections, the connection resistance may however not be reduced due to a geometrical (statistical) size effect [2]. Recommendations for minimum overlap lengths and adhesive layer thicknesses in lap-shear joints are provided.

6. Concluding remark

The TS clauses about fatigue and detailing are complemented by their corresponding background, comprised in the Commentary document [2], which provides the bases and justifications for the decisions taken and values selected.

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