Developments in Dutch FRP design guidance for FRP in infrastructure

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Summary

Around the world the number, size and level of complexity of FRP structures in infrastructure increases rapidly, and it is seen that also for traffic bridges and lock doors FRP is selected in commercial projects. The main challenge in design guidance is the fact that FRP can be made by many different processes with varying degrees of automation. So how can we deal with this variety? How do we take the limited experience branch wide into account? The CUR 96 [1] is the Dutch Design Guidance for FRP in Infrastructure (2003). It is currently being revised into Eurocode format and chapters are added dealing with aspects such as quality control and design verification by tests. The partial factors of the CUR96 guidance were compared to material test data on samples that have been exposed to water for 10 years. Due to the limited number of samples this cannot be considered as a full calibration but allows for a valuable assessment of the validity of the factors.

Keywords: FRP structures, design guidance, partial factors, FRP test, durability.

1. Introduction

Around the world different examples of Fiber Reinforced Polymer (FRP) bridges and buildings are realised, demonstrating FRP’s potential. The size and level of complexity of FRP structures increases. In the Netherlands, at present FRP footbridges are a standard product, but also for traffic bridges, lock doors FRP is selected in commercial projects.

FRP can offer lightweight solutions where concrete and even steel are too heavy, reducing risks and traffic hindrance in the installation phase. FRP structures are very low maintenance and resistant to water and salt. Furthermore FRP’s freedom in form and the translucency can inspire architects to new designs and FRP is seen among others in beautifully curved roofs, cladding, façade panels and viaduct edge elements.

The lack of design guidance results in additional effort and discussion and reduces the efficiency in the design and realisation process of FRP structures. Design guidance is called for by engineers and clients: a uniform design standard will contribute to increased transparency, reliability and efficiency of FRP designs.

The main challenge in design guidance is the fact that FRP is not just one material. It can be made by many different processes with varying degrees of automation. Worldwide, the FRP guidance for pultruded profiles is most complete. But what about moulding techniques? Looking at yacht building and wind energy, it is seen that FRP is well suited to create integrated (curved) shells structures. So how can we deal with all these different fibers, resins, lay ups and manufacturing
processes? How do we take the limited experience branch wide into account?

This paper discusses the development of design guidance for FRP in load bearing structures for buildings and infrastructure.

This work is part of the process of updating the Dutch FRP design recommendation to fit the Eurocode methodology as well as the need for design guidelines of all user groups, from engineers to approving bodies. Reliability is more than just partial factors and design rules. Chapters are added dealing with the installation of FRP structures, quality control and design verification by tests. The partial factors of the CUR96 guidance were compared to material test data on samples that have been exposed to water for 10 years. Due to the limited number of samples this cannot be considered as a full calibration but it does allow for a valuable assessment of the validity of the factors. This initiative is supported by the Dutch Ministry of Infrastructure, research institutes and a large number of industrial partners.

In Chapter 2 to 4 the Revised CUR96 is discussed for the different design stages and purposes. In Chapter 5 the results of the test programme are presented and related to the Design Guidance and especially for the partial factors.

2. Recommendation for the Design of FRP structures

At present, people involved in infrastructure have in general limited knowledge of and experience with FRP. More than for steel, wood or concrete it is important to provide reference data that can be used in the design of FRP structures. Even if any design itself must be executed by a properly knowledgeable engineer it is important that for example senior engineers with experience in other materials can assess the FRP design.

The nature of the FRP material, with its dependency on production process parameters, asks for a determination of mechanical properties by tests. The essence of designing FRP structures is that the material, or rather, the fiber orientation can be optimised for its loading, which would mean that the costs of testing will be very high. Or alternatively, in order to be economical in a start up market, FRP design will be suboptimal to limit costs and efforts. However, global dimensions of designs are in general driven by the serviceability limit state and thus stiffness rather than strength. Depending on the complexity of the design and with the exception of critical aspects such as connections or, it can be argued whether a full characterisation of the specific FRP is needed for each design.

Well established models exist for the prediction of stiffness of FRP materials in fiber dominated directions and these can be used in the design stage, to assess for example, the feasibility of an FRP alternative to steel or concrete and establish the principal dimensions of a structure.

It is the approach of CUR96 to allow the use of theoretical models in the design stage and require tests only for these aspects that prove to be critical in the design or for which no sufficiently reliable theoretical models exist.

This approach allows for an efficient feasibility assessment and design of an FRP structure, and suits the need of the current state. However, measures are needed throughout the design and realisation process to ensure the required reliability is indeed achieved. In the following the method and these measures are further discussed.

The members of the Commission for the Revision of the CUR96 are introduced in chapter 6. Main sources used are [2] – [5].

The Revised CUR96 recommendation has a similar outline to EN1992 [6] and EN1993 [7]. In addition separate chapters are added to deal with design of joints, detailing, the realisation phase and a separate annex is included to give guidance on testing of FRP as part of design and quality control. Another annex describes the aspects of FRP related to environmental impact in an informative set up. With respect to the CUR96:2003 edition more guidance and emphasis is put on tests, as it was seen that in practice in general people have limited experience in executing,
interpreting or designing tests and the use of EN1990 [7], Annex D. The commission of experts and authors of the Revised CUR96 recommendation also contribute to the development of the Technical Report that will form a basis for the Eurocode FRP.

2.1 Engineering data

It is important to recognise the limits of FRP material model theory: models for the prediction of fiber dominated stiffness properties are quite reliable; models for matrix dominated stiffness, such as a transverse stiffness or shear stiffness of a UD-ply are less reliable. The same holds for strength data. Initial strength and stiffness data provided in the CUR96 is conservative and reflects the variability of the specific property due to process defects that can be expected, in the characteristic values as well as the partial material factors (see 2.2).

A characteristic of FRP design is that the determination of the material (i.e. fibers and lay-up) is part of the design process. From a cost and material efficiency point of view, as with concrete, the level of reinforcement needed is preferably based by the design loads on a ply level, rather than specifying distinctive laminate modules.

It cannot be argued that the accuracy of a reference material data set of laminate modules that have been extensively tested (such as DIN 18820 [10]) is high. However, in practice the strength of the laminate will be influenced by the actual materials used, sizings, resins, process parameters such as humidity levels, temperature, etc. Materials, and especially fibers, and sizings are still under development and constantly improved. New fibers, such as natural fibers will become available for use in load bearing structures. It is the opinion of the Revised CUR96 commission that this stage of evolution and development of technology is better served by a more flexible approach.

The CUR96 approach towards engineering design data is that the difference between an approach based on ply data in combination with existing FRP models for materials (such as Tsai Azzi), laminates (Classical Laminate Theory) and failure criteria (Tsai Hill, Tsai Wu, Puck) and an approach fully based on characterised ’standard laminate approach’, can be overcome by the application of a (conservative) model factor. The FRP material models are assumed to be common knowledge and are not further clarified in this paper.

The Revised CUR96 stimulates the use of data derived from tests by allowing for a lower partial model factor, and requires tests for these laminate built ups or characteristic aspects for which theoretical models are not available or considered not sufficiently reliable. Standardization of laminate built ups will happen automatically because of economic arguments, but rather on a supplier or application level than on a guidance level. Furthermore in the realisation stage of the project it is required that it is demonstrated that the design values or the assumed performance of the FRP have been realised.

2.2 Partial factors

In line with the Eurocodes, in the Revised CUR96 the following material related partial safety factors are introduced:

- Partial Material factor \( \gamma_M \)
- Conversion factors \( \eta \)

The design value for resistance \( R_d \) must be calculated from:

\[
R_d = \frac{\eta \cdot R_k}{\gamma_M} \quad (1)
\]

Where:
*R*<sub>d</sub> is the design value for resistance;
*R*<sub>k</sub> is the characteristic value of the particular resistance determined with characteristic values for the material properties and dimensions
*γ*<sub>M</sub> is the partial material factor for the specific resistance
*η*<sub>c</sub> is the conversion factor that takes into account the influence of climate and ageing

### 2.2.1 Partial Material factor *γ*<sub>M</sub>

Besides effects of variation in material properties, the partial material factor *γ*<sub>M</sub> takes into account model uncertainties and geometrical deviations. The following applies:

\[
γ_M = γ_m \cdot γ_{Rd}
\]

Where:
- *γ*<sub>m</sub> is the partial material factor;
- *γ*<sub>Rd</sub> is the partial factor which includes the uncertainties in the resistance model as well as the geometrical deviations;

The material factor *γ*<sub>m</sub> is directly related to the coefficient of variance (*V*<sub>x</sub>) of the mechanical properties. Preliminary a distinction has been made for coefficients of variance up to 0.10 (*γ*<sub>m</sub> = 1.2) and for values up to 0.17 (*γ*<sub>m</sub> = 1.5). Typically, fiber dominated properties of well controlled FRP processes fall into the first category.

The partial factors *γ*<sub>Rd</sub>, *γ*<sub>m</sub> are comparable to the original factor *γ*<sub>m1</sub> and *γ*<sub>m2</sub> respectively in the current Recommendation CUR96:2003. As a reference it can be seen that the factor *γ*<sub>m</sub> is actually of the same level as the factors as mentioned in BÜV:2010, annex E [3]. The difference between Revised CUR96 and BÜV:2010 exists in the addition of a model factor in the CUR96.

Separate partial factors are derived for phenomena with different coefficient of variance, such as connections, local stability and global stability.

The new definition of the partial material factor more precisely indicates which aspect is covered by which factor and stimulates the correct use. In future when material models have been further improved and more extensive nominal material data based on tests has become available, the model factor can be reduced.

### 2.2.2 Conversion factor *η*

The total conversion factor for verifying limit states must be calculated from:

\[
η_c = η_{ct} \cdot η_{cm} \cdot η_{cc} \cdot η_{cf}
\]

where:
- *η*<sub>c</sub> is the total conversion factor to be taken into account;
- *η*<sub>ct</sub> is the conversion factor for temperature effects;
- *η*<sub>cm</sub> is the conversion factor for humidity effects;
- *η*<sub>cc</sub> is the conversion factor for creep effects;
- *η*<sub>cf</sub> is the conversion factor for fatigue effects.

All factors apply to the serviceability limit state. The factor for creep is only applicable to long term loading. The factor for fatigue compensates for a potential loss in stiffness due to micro cracks under fatigue loading. In the Ultimate Limit State (ULS) only the factors for temperature and moisture apply. Fatigue is dealt with in a direct fatigue strength analysis (i.e. Miner summation). Long term loading in the Serviceability limit state (SLS) is verified in relation to creep by a
conservative creep model. In the ULS long term loading is verified in relation to stress rupture, to be verified by means of tests. A development with respect to the CUR96:2003 is that the degradation factors for the influence of moisture and temperature are also related to the glass transition temperature (Tg) of the resin and the service temperature. A difference of 40 degrees or more allows for a reduced factor.

2.3 Stability

The challenge for stability analysis is the fact that most models for buckling of FRP only describe the ideal structure. Design guidance with respect to the inclusion of imperfections is very limited. An important addition of the revised CUR96 recommendation is the inclusion of reference values for imperfection that can be used in design and quality control. For pultrusion profiles reference is made to EN13706 [11]. For other structures the same values for out of straightness are taken as a reference. Different values can be assumed in the design but in the production phase it must be verified that the produced structure is within geometrical tolerances. An important source that reflects the state of the art in pultrusion to the Eurocode methodology is [12]. For profiles this theory is applicable, but still quite complex. Conservative reduction factors are presented for simplified analysis, for different buckling modes. For the analysis of shell structures imperfections must be included also, but no standard is existing as yet to limit geometric imperfections. For FE-analysis a method is developed similar to the method presented for steel shell structures (EN1993-1-5 [9]).

2.4 Connections

The Revised CUR96 allows both adhesive connections as well as mechanical connections in FRP structures. Because of the brittle and progressive nature of its failure for adhesive connections it is required that when failure of the connection leads to dangerous situations or collapse of the structure, a second load path must be foreseen as a backup. Bolted connections must be designed to be critical on bearing failure. Analytical models for predicting the strength of bolted connections are not sufficiently reliable. The effects of hole diameter to thickness or layup variations cannot be considered sufficiently reliable. The design of connections must be supported by test data representative for that specific detail. This may be a test that was performed in a previous project, since the test is meant to empirically support the theoretical model. Analytical models for predicting the strength of adhesive connections are either too simplified or extremely complex and time consuming, involving fracture mechanics. Many aspects relevant to the strength of the connection and especially the influence of manufacturing variances are not included. To include these effects the design must be supported by tests. These can be coupon tests or component tests, or a combination of both. Important requirement is that the tested coupons are representative for the actual adhesive bond, i.e surface treatment, thickness variations, stiffness ratio between adherents, etcetera.

3. Guidance for Design Verification of FRP structures

Design verification involves different aspects, such as:

- Verification of the design calculations
- Verification of the design values or characteristic values
- Verification of the realised structure (geometry, imperfections, performance)
- Design approval (building authorities)

The design verification is usually performed by an independent engineer, in some cases from the same company as the lead engineer of the structure. In the Revised CUR96 in addition to the engineering rules, verification procedures are given. For each product the following tests must be
carried out on at least 5 test specimens each time for at least the following properties:

- tensile test in conformity with ISO 527 or ASTM 3039 to determine the tensile strength and the elasticity modulus;
- ILSS test in conformity with ISO 14130 or ASTM 2344, to determine the ILSS;
- Tg test in conformity with ISO 11357 or ASTM 7028, to determine the momentary $T_g$.

The characteristic value determined in the test must be at least equal to the characteristic value applied in the design. If a lower value is found, the design must be modified accordingly. In the case of a batch or automated production process, such as pultrusion, the tests per product can be replaced with a test programme with material inspection and lower test frequency, providing it is demonstrated that the required confidence level is assured.

4. **Guidance for Installation of FRP structures**

4.1 **Qualified personnel**

An important basis of reliability is that all activities from design to realisation (quality checks, to manufacturing or handling during installation) are done by sufficiently qualified people. This is in line with EN1990. For traditional materials this is controlled by experience requirements and certificates. Measures must be determined for each project specifically based on a risk assessment.

In this stage of development of FRP technology in building and infrastructure it is however not unlikely that people, for example transporters, labourers, contractors and building approval authorities, with limited or no experience in FRP have to deal with the material. For FRP due to the lack of certificates it is important that guidance is in place to specify the degree and type of supervision (i.e. trained by, under supervision of or performed by an FRP expert) for the main activities where due to the different nature of FRP or the complexity or craftsmanship the risks on non-conformities are increased. Examples are handling of FRP or the application of adhesive joints.

In future it is expected that more certificates will be in place to be used as a formal proof of competence. Branch organisations are working on this and several certificates for FRP manufacturing as well as adhesive applicators are in place already.

5. **Assessment of validity of partial factors based on test data**

As part of the Revision process of the Recommendation available test data of three projects were analysed and using Annex D of EN1990 the reliability levels of the designs were verified. One of these projects is the Spieringsluis- lock, where in 2000 a set of GFRP lock doors was placed by the Dutch Ministry of Infrastructure. As part of the project an extensive material test programme was executed. FRP panels of the same constitution (glass fiber, polyester resin) as the lock door material were kept in an indoor environment. Two sets of FRP panels were placed in the water at the lock above, on and below the waterline to expose them to the environment. The first set of panels has been taken from the environment to determine the mechanical properties after 13 years of exposure. Three panels were left in place for further ageing. The original test programme was performed on the aged panels (indoor and outdoor) to study the effect and degradation of the material and assess the validity of the partial material factors and conversion factors in the CUR96:2003. Due to the small dimensions of the panels unfortunately a limited number of samples was available for each test such that this study cannot be used as a calibration of the factors.
5.1  Test programme

The following tests have been executed:

<table>
<thead>
<tr>
<th>property</th>
<th>test</th>
<th>property</th>
<th>test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile modulus, strength 0(^\circ), E(<em>1), (\sigma)(</em>{1t})</td>
<td>ISO 527-4</td>
<td>Interlaminar shear 0(^\circ) (\tau)(_{11})</td>
<td>ASTM D2344</td>
</tr>
<tr>
<td>Compression modulus, strength 0(^\circ), E(<em>2), (\sigma)(</em>{2t})</td>
<td>ISO 604, ASTM D6641</td>
<td>Interlaminar shear 90(^\circ) (\tau)(_{23})</td>
<td>ASTM D23 44</td>
</tr>
<tr>
<td>Tensile modulus, strength 90(^\circ), E(<em>1), (\sigma)(</em>{1t})</td>
<td>ISO 527-4</td>
<td>In plane shear modulus and strength (G)(<em>{12}), (\tau)(</em>{12})</td>
<td>ASTM D7078</td>
</tr>
<tr>
<td>Tensile modulus, strength 90(^\circ), E(<em>2), (\sigma)(</em>{2t})</td>
<td>ISO 527-4</td>
<td></td>
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For each property and climate (dry, waterline, water) only 2 samples could be tested.

5.2  Evaluation of results of EN1990- Annex D

In statistics distinction is made between the situations where the coefficient of variance is known or unknown. In case of FRP the \(V_X\) status is somewhere in between: the level of test data available is insufficient to qualify is a known status, but not fully unknown either. However, because of the limited number of samples, the data cannot be analysed under the assumption of \(V_X\) is unknown. The data was therefore analysed using EN1990, table D.1; \(V_X\) known. The \(V_X\) found from the tests was in all cases within the expected range.

From the lock door project, aged samples were available that have been exposed to outdoor, waterline and water climate. Least regression was found in the outdoor samples. It was seen that the waterline samples more closely resembled the properties of samples exposed to water. For the stiffness properties a reduction of approximately 5 % were found (outdoor) up to 15% (water). For the strength of the FRP the average values showed 0 (outdoor) to 17% (wet) reduction, but the variation was very large.

It was seen from the test results that all characteristic strengths as derived according to EN 1990 table D.1 are equal to or higher than the characteristic strengths according to CUR96:2003. All design values according to EN 1990 table D.2 are significantly higher than design values according to CUR96:2003. CUR96:2003 is therefore considered conservative.

The samples that were exposed to the outdoor environment and to the water are used to assess the validity of the conversion factors. Because of the limited number of samples per test, the evaluation is based on the average values.

It was seen from the tests that the effect on stiffness is in general lower than covered by the conversion factors. Degradation of mechanical strength was not only seen in resin dominated properties such as ILSS, but also in tensile tests in main fiber direction. The degradation on tensile strength was larger than the degradation in compression tests.

The degradation of properties exposed above the waterline (outdoor climate) was less than covered by the conversion factors. For the samples exposed to water the effects on strength covered by the conversion factors were conservative, but the margin was considered too small with respect to the ageing period. Because of the large margin of safety in the partial material factors, the reliability of the design is sufficient. However, more tests on exposed material are recommended and necessary
to further verify the validity of the conversion factors.

5.3 Conclusion

The partial material factors derived from the tests according to EN 1990 annex D are in all cases lower than the partial factors as part of the CUR96:2003 and the Revised CUR96. Based on the analysis there is no reason to assume that the current partial material factors are not sufficiently conservative.

For the serviceability limit state design as well as for outdoor applications there is no reason to assume that the current conversion factors are not sufficiently conservative. For the ultimate limit state design for applications exposed to water further research is recommended to verify the validity of the conversion factors.

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7. References