ON DESIGN AND EXPERIMENTAL VERIFICATION OF ACTUAL BEHAVIOUR OF SELECTED ALL-FRP STRUCTURAL COMPONENTS FOR CIVIL ENGINEERING

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ABSTRACT

Based on the research and design activities conducted at Brno University of Technology, Czech Republic, this paper deals with basic information on problems of design and actual behaviour of the selected all-FRP structural components for civil engineering. In particular, the recorded experimental studies are focused mainly on the design assessment of fibre-glass grid flooring components. The design criteria for structural FRP parts of load bearing systems should verify especially the final displacements. Thus, in general, the ultimate limit state of structural system is not only the problem of ultimate strength but namely the problem of accordant final displacements. The analysis of test results gives data for the verification of numerical modelling and for the checking of conventional design criteria. Considering the specific character of structural all-FRP systems, for the structural design the recognition of the deflection advancement can be decisive.

KEYWORDS

FRP, fibre-glass grid, vacuum test method, inverse design method, ultimate strength, design strength.

INTRODUCTION

In the last two decades the extensive development of advanced structural systems for civil engineering works were characterized by the application of wider spectra of basic materials used for load-bearing structural components. Thus beyond traditional materials such as reinforced concrete, masonry, steel and timber also the fibre-reinforced polymers have become a basic generating substance of structural parts and systems.

Over the past period, there have been significant developments in composite processing methods such as pultrusion, filament winding, resin transfer molding and resin infusion molding. These methods use different fiber reinforcement for different applications. Nowadays, higher quality FRP materials are available in more attractive shapes and forms for civil engineering. The contemporary challenge is to make them more cost effective for different constructional components. The mechanical properties of FRPs make them convenient for widespread applications. Being noncorrosive, nonconductive and lightweight the fiber-reinforced polymer composites have desirable properties for extreme environments. They are also noted for sufferable souse in drinking water-stations or sewage disposal plants. There are three broad divisions, into which utilization of FRP in civil engineering can be classified, namely: application for new construction, repair and rehabilitation, and architectural implementation.

Within recent years, a substantial attention to problems of design, application and experimental verification of the structural load-bearing components made of FRPs has also been paid in the Division of Metal and Timber Structures at the Brno University of Technology, Czech Republic. Our studies are based on production and provider activities of the firm PREFA KOMPOZITY, Joint-Stock Co., Brno. In that manufacturer firm different production technologies for the fabrication of structural members and components are used, namely: pultrusion, pipe winding, horizontal casting and hand laminating. Large set of products (bars, open and hollow shapes, grids, plate covers, etc.) facilitate the composition of footbridges, culverts, boards, stairs, railing, anti-noise screens, frame and flooring systems, façade elements and others, especially for buildings, transport construction, industry, water utilization, power and chemical engineering.
Some typical examples of FRP elements and construction products of the aforementioned producer are presented in Figure 1 (flooring beams, grids and columns of attendant platforms and gangoards in a sewage works) and Figure 2 (piers on a lake with swimming pool).

Lately, the development of the alkali activated composite materials (geopolymers) has been emphasized - see Prokes (2007), for example. Such materials are expected to substitute composites with organic matrix as epoxy, unsaturated polyester or phenolic resins. Glass and carbon fiber reinforced composites with alkali activated matrix will be used in the construction sector, especially for buildings and technologies with demands on inflammability and fire endurance. The geopolymers have excellent heat and fire resistance, nevertheless their mechanical and chemical properties are relatively poor in comparison with organics polymeric matrixes and need more attention and improvement in future.

The design practice of FRP structural elements and systems can utilize the knowledge and experience generated in the field of traditional structural materials, nevertheless different properties and behaviour of FRP conduces to modification of analysis and design approaches backed by experimental verification. Further, in terms of that reflection some ideas will be illustrated.

NOTE TO DESIGN CONCEPT OF STRUCTURAL COMPONENTS MADE OF FRP

In general, the contemporary approach to structural design of load-bearing members and systems for buildings and civil engineering is based on the limit state concept, i.e. on LRFD (Load Resistance Factor Design). The reliability expressed through the relation of the defined extreme (maximum) effect of load actions to the defined extreme (minimum) member resistance necessitates one universal and systematic design concept for all kinds of structural materials. Thus, at present, the respective standards or design codes for FRP structures are generated in different countries and regions, such as through the ASCE in collaboration with the ACMA (American
Composites Manufacturers Association) within a project announced for the period of 2007 – 2009 or through CEN (Comité Européen de Normalisation) within the project of EUROCODEs. Current technology and design information is elaborated by Bank (2006), for example.

Also with FRP components the ultimate limit states can prove the structural safety based on the verification of their strength, stability, fatigue and structural failures in general. For the illustration, in Figure 3 the example of failure of the fixed end at ultimate bending strength of a short composite fibre-glass cantilever is presented.

![Illustration of failure mechanism at ultimate state of a composite fibre-glass cantilever](image)

Nevertheless, because of the very low rate of elasticity modulus to member strength (comparing with steel and concrete, for example), the deformation design criteria of FRP are often decisive for the resulting component dimensions. Their final displacements or deflections at ultimate strength can be so large that the corresponding ultimate state is outside the real member behaviour. Then the deformation criteria should be used to assign the design load-carrying capacity in terms of ultimate limit state, as well.

The problem of deformation criteria with respect to the ultimate limit state (characterized by small and developed plastic deformations, final real displacements, excess shifting in joints, opening of cracks, creeping of joints and ductility characteristics, for example) was discussed by Melcher (1996).

![Angle of twist Φ under torsion of a single and built-up strut](image)

Actually at steel structures that problem can be noted, too. In Figure 4 the conformable example aimed at the verification of torsion rigidity is presented. The test conducted by Melcher (1987) refers to a single steel angle member 50x50x4 mm compared with built-up double angle specimens of T-section with intermediate single 10 mm gusset end plates and two (2F), three (3F) and four (4F) square fillers uniformly placed along a strut. Transverse couple forces $P_t$ with a lever arm of 600 mm were placed on both ends of a 2000 mm long strut. The torsion rigidity test depreciates the corresponding ultimate strength in terms of ultimate limit state.
Based on the previous deliberations the ultimate strength design approach should be completed by verification of final ultimate characteristics of displacements and deformations. So for the required or prescribed ultimate deflection $\delta_u$, permanent plastic strain $\varepsilon_p$ or other deformation characteristics, the corresponding design (specified) strength $P_\delta$ or $P_\varepsilon$ could be less than the ultimate limit state capacity based on ultimate strength. This design approach, called inverse design method, is illustrated in Figure 5.

![Figure 5. Scheme of inverse design method](image)

Especially at FRP beam and plated components the transversal actions evocate large deflections without noted material failures. Thus the ultimate strength could be a subject of knowledge or complex model analysis but for the practical design purposes the problem can be reduced to the verification of stiffness and displacements caused by action advancement. That approach was used at the tests of FRP grids described briefly in next article.

**EXPERIMENTAL VERIFICATION OF ACTUAL BEHAVIOUR OF GRIDS MADE OF F-GLASS RP**

In Figure 6 different types of FRP grids right for attendant platforms, gangoards, industrial flooring or pier decking are presented, namely: PREFAPOR walk-able grids (produced by PREFA KOMPOZITY firm) assembled of pultruded Π-sections or I-sections gathered by transverse round bars (Figure 6a and 6b) and PowerGrid (imported from P.R.C.) or PREFAGrid walk-able grids made by shape casting and pressing.

To simulate the behaviour of a grid under uniformly distributed load, an experimental procedure referred to as the vacuum test method was utilized (Figure 7). The method involves producing a vacuum under the test specimen covered by clear plastic stuck to the floor of the laboratory, and then measuring the difference in pressure between the outside atmospheric pressure and inside the enclosed rigid test frame - for more see Melcher (1997), for example.

![Figure 6. Types of fiber-glass composite grids](image)

For the illustration some test results are presented in Table 1. The conclusions refer to selected types and proportions of grid specimens under uniformly distributed load. The values of the equivalent stiffness $EI_b$ of the grid relate to the plated strip width of $b = 1000 \text{ mm}$. The stiffness characteristics were derived from test data indicated graphically in Figure 8.

Considering the equivalent stiffness makes it possible to avoid the tough problems of assessment of the grid section properties depending on geometry, composition and reinforcement technology effects.
Figure 7. Verification of a fiber-glass composite grid behaviour under uniformly distributed load

Table 1. Equivalent stiffness $E_{lb}$ of grid specimens for plated strip width of $b = 1000$ mm

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Grid notation</th>
<th>Grid rectangular opening [ mm ]</th>
<th>Depth [ mm ]</th>
<th>$E_{lb}$ [ N . mm$^2$ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 10</td>
<td>PowerGrid</td>
<td>20x95 / 25</td>
<td>20x95</td>
<td>54.185 * 10$^8$</td>
</tr>
<tr>
<td>T 11</td>
<td>PowerGrid</td>
<td>30x30 / 25</td>
<td>30x30</td>
<td>29.278 * 10$^8$</td>
</tr>
<tr>
<td>T 12</td>
<td>PowerGrid</td>
<td>32x32 / 38</td>
<td>32x32</td>
<td>87.123 * 10$^8$</td>
</tr>
<tr>
<td>T 01</td>
<td>PREFAGrid</td>
<td>30x30 / 14</td>
<td>30x30</td>
<td>5.7184 * 10$^8$</td>
</tr>
</tbody>
</table>

Figure 8. Relation of uniform load $p$ [kPa] to corresponding maximum deflection $w$ [mm]
SIMPLIFIED GRID DESIGN PROCEDURE

Based on the aforementioned note to the design concept of structural components made of FRP, the criterion defining the limit design load (in terms of ultimate limit state) for grid components under consideration can be introduced in the terms of

\[ w [\text{mm}] \leq w_u, \]

where \( w [\text{mm}] \) is the maximum grid deflection under design load derived using the equivalent stiffness verified by experiments,

\( w_u \) is defined ultimate grid deflection given by the settlement of a client and a contractor.

For the walk-able grids of the span \( L \) the defined ultimate deflection \( w_u \) should be such as

\[ w_u = \frac{L}{150} \leq 6 \text{ mm}, \]

when the ultimate value of 6 mm corresponds to the conventional requirement on ultimate deflection \( w_u = 0.25 \) inch (i.e. 0.25 * 25.4 = 6.35 mm) generally used in the U.S.A. for similar cases – see Extren Design Manual, Strongwel Co., for example.

CONCLUSIONS

- The extensive development of advanced structures can be characterized by the application of wider spectra of basic materials. Thus beyond traditional materials such as concrete, masonry, steel and timber also the fibre-reinforced polymers have become a basic generating substance of structural systems.
- The fiber-reinforced polymer composites have desirable properties for extreme environments because they are noncorrosive, nonconductive, and lightweight. They are also noted for sufferable souse in drinking water-stations or sewage disposal plants.
- Because of the very low rate of elasticity modulus to member strength (comparing with steel and concrete, for example), the deformation design criteria of FRP are often decisive for the resulting component dimensions. Their final displacements or deflections at ultimate strength can be so large that the corresponding ultimate state is outside the real member behaviour. Then the deformation criteria should be used to assign the design load-carrying capacity in terms of ultimate limit state, as well. Thus, in general, the ultimate limit state of structural system is not only the problem of ultimate strength but namely the problem of accordant final displacements.
- Considering the experimentally verified value of equivalent stiffness makes it possible to avoid the tough problems of the assessment of the grid analysis considering the section properties depending on geometry, component composition and reinforcement technology effects.

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