1. INTRODUCTION

Current tendencies in Hungary show a shortage of labour in the construction industry which requires the application of less labour-intensive structural solutions. The application of fibre reinforced concrete for prefabricated structural members is a promising way to reduce the demand for labour of reinforcement assembly and speed up the construction process.

Results of the monitoring of existing structures [1] show the advantages of fibre reinforcement in the field of structural durability, too. According to the detailing rules of EN 1992-1-1 standard (EC2), a minimum amount of stirrups must be applied as shear reinforcement in reinforced concrete beams. This kind of “conventional” shear reinforcement can be, however, decreased below the required minimum, or it may be...
even completely neglected by the application of proper fibre reinforcement. The objective of our research was to find out whether the use of fibre reinforced concrete mixture could partially or fully replace the conventional shear reinforcement in prefabricated beams for industrial halls. The concept of using fibres as reinforcement is not new; they have been used as reinforcement since ancient times. Fibres are usually used to increase ductile behaviour of concrete, control cracking due to plastic and drying shrinkage, reduce bleeding of water and permeability of concrete, and produce a better resistance against dynamic impacts. Generally, fibres do not increase the flexural strength of concrete beams, however, shear strength can be significantly improved as tensile strength of the concrete is increased by the application of fibre reinforcement [2, 3, 4, 5, 6]. The present research was preceded by previous studies. To find the fibre type that is best suited to the objective set in terms of performance, workability and efficiency an extensive experimental program was carried out at the Laboratory of Materials and Structures, Budapest University of Technology and Economics [7]. Another experimental program was also carried out at the Structural Laboratory of Budapest University of Technology and Economics between 2014 and 2015. In this experimental program the shear strength of small span (6 m), prefabricated, prestressed beams without stirrups, but with variable fibre type and content were tested [8]. During the current research, we focused on the shear capacity of larger span (12–25 m) prefabricated, prestressed FRC beams with sparse stirrup spacing (applying stirrups at the ends of the beams only) or without shear reinforcement. Within the frames of the research, the shear strength of several beam specimens was tested, and the analytical and numerical analyses of these beams were also performed.

2. INTRODUCTION OF THE TESTS

2.1. Tested beam specimens

In frames of the research four different prefabricated, prestressed FRC floor beams were studied. Beam types T70 and T140 have variable height T sections, beam type T90 has constant height T section and beam type R70 has constant height rectangular cross-section that works together with an in-situ reinforced concrete slab in the final state. Shear reinforcement was completely neglected for beam type T90 while other beams included stirrups with partially sparse spacing (compared to the requirements of EC2) at their support region only. In each beam, Dramix steel fibre reinforcement was applied. Typical shapes, cross-sections and main dimensions of analysed beams are illustrated in Fig. 1. Applied concrete grade, longitudinal reinforcement and fibre dosage of different beams are shown in Tab. 1.
During the tests, fork supports were used at both ends of the beams according to the usual construction solution. For beam types T70, R70 and T140 the load was applied step-by-step using verified weights that were put on the beams in predetermined points. In each load step, the deflection of the examined beam was measured by mechanical dial indicator placed in the middle of the span. To avoid the complete destruction of the beams they were loaded only up to ~80% of their load carrying capacity calculated on the mean level. Beam type T90 was tested on a test stand. In this case the asymmetrically applied concentrated force (Fig. 2) was produced by a hydraulic jack and the deflection of the beam was measured in the middle of the span as well as under the acting force. This beam was also loaded up to ~80% of its calculated carrying capacity only to avoid the collapse. Before performing the load test on the beam, its concrete strength was determined by conducting non-destructive Schmidt hammer tests in 10 locations along the web and in 5 locations along the flange. The measured concrete compressive strength values were considered for the numerical analysis of the beam [9].

### Table 1.
Dimensions, material grades and longitudinal reinforcement of tested beams

<table>
<thead>
<tr>
<th>Type of beam</th>
<th>T70</th>
<th>R70</th>
<th>T90</th>
<th>T140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length L [m]</td>
<td>11.96</td>
<td>14.36</td>
<td>19.00</td>
<td>24.67</td>
</tr>
<tr>
<td>Heigh (at midspan) h [m]</td>
<td>0.70</td>
<td>0.70</td>
<td>0.90</td>
<td>1.40</td>
</tr>
<tr>
<td>Concrete grade (prefabricated girder)</td>
<td>C40/50</td>
<td>C40/50</td>
<td>C50/60</td>
<td>C50/60</td>
</tr>
<tr>
<td>Dramix fibre volume [kg/m³]</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Longitudinal reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>2φ16 + 2×Fp52-1860</td>
<td>4×Fp52-1860</td>
<td>4×Fp52-1860</td>
<td>2×Fp52-1860</td>
</tr>
<tr>
<td>Design load p_d [kN/m]</td>
<td>25.34</td>
<td>38.28</td>
<td>18.9</td>
<td>32.92</td>
</tr>
</tbody>
</table>

2.2. Results of the tests

Measured shear force – displacement diagrams are presented in Fig. 3. The shear force acting at the support was always calculated from the actual load arrangement and intensity in each load step. In case of the tested beams the measured shear capacities were higher than the corresponding design shear forces. However, it does not automatically mean that the shear strength of FRC beams is satisfactory on the same reliability level as the beams with conventional shear reinforcement. According to our previous studies [8], FRC beams with even higher fibre content (35 kg/m³) have a higher probability of shear failure than the control beam containing stirrups as shear reinforcement. Because of the insufficient number of specimens, the shear reliability of the tested beams could not be directly determined. It is planned to test further beams in the future so statistical evaluation of the results can be also carried out. The results of current tests were nevertheless used, on the one hand, to verify the results of analytical calculations and, on the other hand, to calibrate the numerical model.
3. ANALYTICAL VERIFICATION OF THE BEAMS

3.1. Shear strength of FRC beams

EC2 does not provide guidance on the detailed analysis of fibre reinforced concrete structures, therefore the effect of fibre reinforcement on shear strength was considered on the basis of the Steel Fibre Concrete Directives from German Committee on Reinforced Concrete [10], which also conforms to the Eurocode standard system. According to the DAfStb directives, steel fibre reinforced concrete beams can be classified into the strength classes L1 and L2 based on the characteristic bending-tensile strength that can be measured after the cracking of the concrete. The L1 performance class delivers the characteristic post-cracking bending-tensile strength of concrete in serviceability limit state, while class L2 stands for post-cracking bending-tensile strength in the ultimate limit state. The additional shear strength that is provided by the steel fibres can be calculated from the design centric tensile strength:

\[ V_{Rd,cf} = f_{cfd,1} \cdot b_w \cdot h \]  

where \( b_w \) is the web thickness and \( h \) is the overall height of the beam. The additional shear strength provided by the fibres can be summarised with the shear strength of concrete to obtain the total shear strength of the concrete cross section. The shear resistance of the member without shear reinforcement is satisfactory if the following criterion is fulfilled [11]:

\[ V_{Rd,c} + V_{Rd,cf} \geq V_{Ed} \]  

where \( V_{Rd,c} \) is the design shear resistance of the member without shear reinforcement calculated according to EC2, and \( V_{Ed} \) is the design value of the applied shear force.

The performance class of an FRC beam is influenced by several factors [12] and it can be determined by the evaluation of appropriate test results according to DAfStb directives. However, in our situation, the performance class of the tested beams was not determined by the manufacturer, only the amount and type of applied fibres were known. Therefore, the performance class of the tested beams was determined based on empirical data available in the relevant literature [13]. The centric tensile strength was calculated for the tested beams according to the DAfStb directives, considering the appropriate concrete grades and fibre volumes [14]. The calculated values of centric...
**3.2. Results of analytical calculations**

Compliance of the tested beams was verified by analytical calculations according to EC2. Initial prestress in the tendons was calculated from the 110 kN tensioning force that was applied by the manufacturer for the construction of the members. Concrete and steel stresses were verified in the initial state \( (t = 0) \). The loss of prestressing force due to shrinkage, creep and relaxation was calculated and the distribution of effective prestress was determined in the final state \( (t = \infty) \). Bending moment resistances of different beams were verified considering the calculated effective prestress values. In case of beam type R70, a 15 cm thick in-situ concrete (grade C30/37) slab was also taken into account for the determination of bending moment resistance. For the verification of shear resistance, the effect of fibre reinforcement was also taken into account. The anchorage region of the tendons was verified for transverse tension taking the shear utilization of the stirrups into consideration. Serviceability limit states, as well as transition states, were also verified [14].

According to the comprehensive study of the beams, we may conclude that despite the reduced amount of conventional shear reinforcement they still meet the requirements in most design situations. However, we encountered some problems with the shear strength, as well as with the transverse tensile strength at the ends of the beams. In the calculations, the load was applied in 20 kN steps to the structure. In ATENA software the widely known AKC-model [15] is allowed the consideration of both conventional and fibre reinforcement, as well as geometric and material nonlinearity for the calculation of structural behaviour. The numerical analysis intended to compare the shear strength of prestressed FRC beams with different amount of steel fibres and also to compare these values to the shear strength of a beam containing the amount of stirrups required by EC2. In the following, the modelling of beam type T90 will be briefly presented.

In the numerical model, fork support was applied according to the usual construction solution. The analyzed beam was symmetrical so it was possible to analyze only the symmetrical half, thus the running time could be speeded up. In the calculations, the CC3DNonLinCementitious2 material model built into ATENA was used to describe concrete behaviour. The beam was modelled by tetrahedral and brick elements, the average mesh size was 0.1 m (0.2 m mesh with 0.5 length coefficient). To have constant shear force distribution on the beam, a concentrated force was applied 2.25 m from the support like in case of the test. The load was applied in 20 kN steps to the structure. In ATENA software the widely known AKC-model [15] is applied.

### Table 2.

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Concrete grade</th>
<th>Fibre volume fraction ([\text{kg/m}^3])</th>
<th>Performance class ((L2) [\text{N/mm}^2])</th>
<th>Actual concrete</th>
<th>Centric tensile strength ([\text{N/mm}^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>T70</td>
<td>C40/50</td>
<td>20</td>
<td>C25/30</td>
<td>0.488</td>
<td>0.631</td>
</tr>
<tr>
<td>R70</td>
<td>C40/50</td>
<td>20</td>
<td>C25/30</td>
<td>0.488</td>
<td>0.631</td>
</tr>
<tr>
<td>T90</td>
<td>C50/60</td>
<td>30</td>
<td>1.001</td>
<td>1.564</td>
<td>0.579</td>
</tr>
<tr>
<td>T140</td>
<td>C50/60</td>
<td>20</td>
<td>0.488</td>
<td>0.736</td>
<td>0.272</td>
</tr>
</tbody>
</table>

In order to have satisfactory structural elements also for shear and transverse tension, the concrete grade, the diameter or spacing of the stirrups and/or the applied fibre volume may be modified. For the studied beams, the concrete grade and the amount of stirrups were left unchanged but an increased fibre volume was assumed (we considered 40 kg/m\(^3\) fibres for beams T70, R70, T90 and 60 kg/m\(^3\) fibres for beam T140). According to the analytical calculations, all beam types would be satisfactory for shear and transverse tension with the increased fibre volumes. Fig. 4 illustrates the utilization of shear strength for beam type T70 with the initial and increased fibre volumes. Results of the analysis showed that the application of the right type and amount of fibres can partially replace the conventional shear reinforcement in prefabricated floor beams. If we want to completely neglect the stirrups from the beams, the fibre volume must be significantly increased, as it will be shown in the next chapter. However, concrete mixing and casting in case of high fibre volumes is still a challenge for the domestic concrete industry.

### 4. NUMERICAL ANALYSIS

The effect of applied steel fibre volume on the shear strength of prestressed beams was analysed using the ATENA v5.1.1 nonlinear finite element software [9], [14]. This software allows the consideration of both conventional and fibre reinforcement, as well as geometric and material nonlinearity for the calculation of structural behaviour. The numerical analysis intended to compare the shear strength of prestressed FRC beams with different amount of steel fibres and also to compare these values to the shear strength of a beam containing the amount of stirrups required by EC2. In the following, the modelling of beam type T90 will be briefly presented.

In the numerical model, fork support was applied according to the usual construction solution. The analyzed beam was symmetrical so it was possible to analyze only the symmetrical half, thus the running time could be speeded up. In the calculations, the CC3DNonLinCementitious2 material model built into ATENA was used to describe concrete behaviour. The beam was modelled by tetrahedral and brick elements, the average mesh size was 0.1 m (0.2 m mesh with 0.5 length coefficient). To have constant shear force distribution on the beam, a concentrated force was applied 2.25 m from the support like in case of the test. The load was applied in 20 kN steps to the structure. In ATENA software the widely known AKC-model [15] is...
K. Koris, I. Bódi

used to predict the stress and strain for the concrete containing fibres. The amount of applied fibres was entered as certain reinforcement ratios in 7 directions. The beam was analysed in 6 different situations. In the first case stirrups fulfilling the requirements of EC2 were applied in the beam. In five more cases the beam was modelled without stirrups, but with variable fibre contents (0, 20, 30, 40, 110 kg/m³). During the numerical analysis the shear force – deflection diagrams and the corresponding shear capacities were determined.

Figure 4.
Shear strength utilization of beam T70 in case of different fibre contents

Figure 5.
Shear force – deflection and shear crack width diagrams of beam T90 in case of different fibre volumes
for each shear reinforcement type. The results of the shear strength are shown in Fig. 5. Based on these results, the shear capacity of the beam increases by increasing the amount of fibre reinforcement, however, 30 kg/m³ fibre content applied in beam T90 is not able to provide the same shear resistance as the stirrups.

It can be seen from Fig. 5 that only a significantly higher fibre dosage (about 75 kg/m³) can provide the shear strength that is equivalent to the shear strength of stirrups. Thanks to the crack bridging effect of the steel fibres, the ductility of the beam significantly increases by the increase of fibre dosage but the width of shear cracks will be still larger than in the case of the beam with stirrups as shear reinforcement (Fig. 5). This phenomenon is mainly caused by the fibres being pulled out from the concrete due to their relatively small anchorage length. Similarly to the shear resistance of the beam, the shear crack width can be efficiently limited by the significant increase of the fibre content. It was also observed during the numerical modelling, that while shear strength can be efficiently increased by the application of proper fibre dosage, the bending moment resistance does not increase considerably even if the amount of fibres is significantly increased. If we increase the fibre dosage from 20 kg/m³ to 110 kg/m³ for the beam T90, the bending capacity is increased by 20% only, while the increase in shear capacity is 81%.

5. CONCLUSIONS

The purpose of our study was to find out whether the use of fibre reinforced concrete mixture could partially or fully replace the conventional shear reinforcement in prefabricated beams for industrial halls. We can conclude that steel fibre reinforcement significantly increases the shear strength of prestressed concrete beams. However, in case of the studied beams, only a significant amount of steel fibre reinforcement (75 kg/m³ or greater) could completely replace the conventional shear reinforcement. The mixing and casting of concrete with such high fibre content can be, however, technologically problematic with the use of the currently available pre-casting technologies. According to the analytical and numerical calculations, it could be a suitable and economical production alternative for prestressed concrete floor beams to provide the shear strength by the mixed application of about 40 kg/m³ steel fibre content and conventional stirrups with sparse spacing only at places that are most utilized for shear. As it is also shown by some foreign approaches (Grunert, Stroback, Teutsch, 2004), a more economical production of such structural elements may be achieved if we completely neglect the stirrups from prestressed concrete floor beams by using high strength concrete mixtures and by significantly increasing the fibre content, which of course requires the development of manufacturing technologies, too.

REFERENCES


