*ENGINEERING TRANSACTIONS* • *Engng. Trans.* • **63**, 4, 407–419, 2015
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM) • Poznan University of Technology

# Prestressing Concrete Structures with CFRP Composite Tendons

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This paper presents a study on prestressing concrete structures with Carbon Fibre Reinforced Polymer (CFRP) tendons. It is an alternative to conventional steel prestressing materials, which distinguishes itself by complete resistance to corrosion, good tensile and fatigue strength and better performance in time under loading. Mechanical properties and examples of prestressing structures with composite tendons are briefly described. The article is focused mainly on describing procedures given by available codes and guidelines. Finally, calculations for an example of a concrete beam prestressed with CFRP tendons are conducted and the results and differences between both codes are presented and summarized.

**Key words:** prestressed concrete, concrete bridge girder, carbon fibre reinforced polymer, CFRP tendon.

## 1. Introduction

As an alternative to conventional prestressing steel strands there are tendons made of fibre reinforced polymer composite materials [13]. They consist of unidirectional fibres, usually aramid, glass or carbon, which are placed in epoxy resin matrix. This paper is focused on CFRP tendons made of carbon fibres. Their basic properties as well as design approaches and partial procedures concerning ultimate limit state design are presented and compared.

The CFRP tendons consist of fibres, which are usually 60–70% of total volume, and they can be divided in two main groups: the former are CFRP single rods and the latter are carbon fibre composite cables (CFCC) (cf. Fig. 1), which consist of several strands twisted together as in common steel tendons. During manufacturing it is possible to shape the surface of CFRP rods in order to improve sufficient bond strength between prestressing reinforcement and concrete.

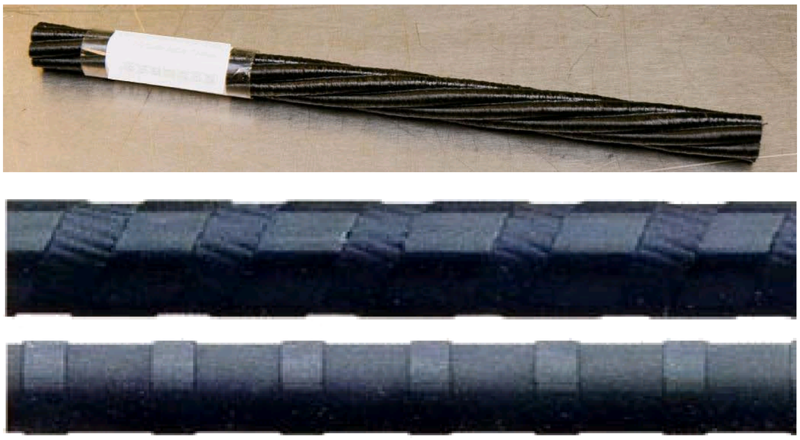

FIG. 1. Examples of CFCC tendon and CFRP rods.

### *1.1. Material properties*

Tendons made of carbon fibres possess numerous advantages, which in some cases can play decisive role during design process of a structure. First of all, their density and therefore self-weight are substantially smaller than for steel strands (density of CFRP is ca. 1.5 g/cm$^3$, for steel strands it is 7.85 g/cm$^3$). Secondly they have very low conductive properties and, above all, they are completely resistant to corrosion [6, 12]. Furthermore, their fatigue strength is significant and their behaviour in time is similar or even better than for low-relaxation steel tendons. The material properties of two types of strands, namely the Leadline rods (produced by Mitsubishi Company) and the CFCC tendons are presented in Table 1.

**Table 1**. Material properties of the two chosen CFRP strands [11].

| Parameter | Leadline rod | CFCC tendons | | |
|---|---|---|---|---|
| Diameter [mm] | 8 | 10.5 | 12.5 | 15.2 |
| Cross-sectional area [mm$^2$] | 46.1 | 55.7 | 76 | 113.6 |
| Tensile strength [GPa] | 1970 | 1725 | 1868 | 1750 |
| Elasticity modulus [GPa] | 147 | 140 | 141 | 138 |
| Maximum strain [%] | 1.3 | 1.7 | 1.6 | 1.6 |

The most distinguishing property of CFRP tendons is their behaviour under loading i.e., composite strands do not exhibit a yielding, as it is with steel tendons. Strands rupture just in the moment of achieving their ultimate tensile strength value, and the failure is brittle, what is often considered a big drawback. However, it is noteworthy to point out that maximum possible stresses in CFRP tendons are larger than in steel, what together with a lower elasticity modulus contributes to higher possible deflections in structures prestressed with CFRP strands. Therefore visible deflections can be considered as indicators of a possible failure and monitoring of deflections is commonly used in the majority of structures prestressed with composite tendons. The CFRP strands are relatively new and not thoroughly known material, and for that reason prestressed structures are usually constantly monitored especially in field applications. In bridges prestressed with CFRP tendons, which have been so far built and opened to traffic in the USA, values of deflections and their increments are regularly examined [4, 6].

### *1.2. Current codes and guidelines*

The first code for FRP reinforced or prestressed structures was published in 1995 in Japan (by Japan Society of Civil Engineers). In 2000 and 2002 two Canadian standards, CAN/CSA S6-00 ("*Canadian Highway Bridge Design Code*") and CAN/CSA S806-02 ("*Design and Construction of Building Components with Fibre-Reinforced Polymers*"), were issued and on their basis ISIS organization (Intelligent Sensing for Innovative Structures, Canadian Network of Centres of Excellence) published a design manual entitled "*Prestressing Concrete Structures with Fibre Reinforced Polymers*" [9]. In the meanwhile, American standard ACI 440.4R-04 "*Prestressing Concrete Structures with FRP Tendons*" [1] was published in 2004 and its revised edition appeared in 2011. These two mentioned codes, ISIS guidelines and ACI standard, will be a subject of the analysis presented in this article. Abbreviations ISIS and ACI are used by authors for documents Design Manual "*Prestressing Concrete Structures with Fibre Reinforced Polymers*" and ACI 440.4R-04 "*Prestressing Concrete Structures with FRP Tendons*", respectively.

### *1.3. Examples of FRP prestressing in engineering practice*

In Europe the first projects aimed mainly at presenting potential and possibilities of composite materials usage for prestressing concrete structures. Two bridges were erected in Germany: the Marienfelde bridge in Berlin in 1988, which was externally prestressed with GFRP, and the BASF bridge in Ludwigshafen in 1991, prestressed with internal steel strands and unbonded CFRP tendons [9]. At the same time, another bridge, called Shinmiya, was constructed in Japan in 1988 and prestressed with CFCC tendons. Noteworthy, until today they do not demonstrate losses of prestressing force and their whole structure is in good condition [10].

An important construction is also a bridge constructed in the United States of America on the basis of researches conducted at Lawrence Technological University by Grace and his team [4, 7]. In 2001 the Bridge Street Bridge was designed and constructed in Michigan with assistance of Professor Grace and Professor Abdel-Sayed of the University of Windsor which was the first structure entirely reinforced with composite materials. Precast beams were prestressed and reinforced with CFRP rods and next, on the construction site, they were post-tensioned with external CFCC tendons. Furthermore, to have a better understanding and comparison of this new technology with conventional one, two

Fig. 2. Execution of the Bridge Street Bridge (top) and fastening of composite tendons (bottom) [4].

similar bridges were built in the same place, one next to the other. The first was prestressed according to description provided above, and the second one had conventional passive and active steel reinforcement. Since then, the deflections and other values obtained from various sensors placed on both constructions are constantly registered and this should last until 2020.

## 2. Prestressing force losses

Similarly to steel tendons, losses of prestressing force applied in CFRP strands are caused by slip of the tendon in anchorages, elastic concrete deformations, influence of concrete creep and shrinkage and relaxation of tendons [5]. According to both ACI and ISIS guidelines all of the losses, except from relaxation, can be calculated using the same methods as for conventional prestressing, obviously taking into consideration differences in material characteristic, such as different elasticity modulus.

The phenomena of relaxation of composite tendons is still not thoroughly recognized, many researches are being conducted to establish valid values for CFRP prestressing strands. Generally, prestressing force losses due to relaxation of FRP tendons are caused by three reasons: relaxation of fibres $R_f$, relaxation of polymer matrix $R_p$ and also by strengthening of fibres $R_s$. Total relaxation according to ACI [1] can be estimated as the sum of the three factors mentioned above.

Relaxation of polymer matrix occurs immediately, during the first days after prestressing, and can be negatively influenced and thus increased when concrete curing is accelerated by heating. The loss of prestressing force due to matrix relaxation is a multiplication of two factors:

$$R_p = n_r v_r, \tag{2.1}$$

where $n_r$ is a ratio of elasticity modulus of polymer matrix to fibres' elasticity modulus ($n_r = E_r/E_f$), and $v_r$ is an amount of matrix in the whole volume of tendon, expressed as a percentage, which is usually equal to around 35%. This relaxation value varies within the range 0.6–1.2% of initial prestressing force.

Relaxation of fibres depends mainly on whether they are concrete, aramid or glass. Concrete fibres in ACI [1] code are said not to show any relaxation at all ($R_f = 0$), however in Canadian guidelines [9] relaxation of fibres can be evaluated with the following formula:

$$REL_3 = 0.231 + 0.345 \log(t), \tag{2.2}$$

where $t$ is a time in days.

The strengthening of fibres ($R_s$) is caused by the fact that fibres in polymer matrix are not entirely parallel to each other and during an application of prestressing force they demonstrate a tendency to move inside the matrix. It can be described as a relaxation loss and is dependent on the quality of manufacturing of the tendons, remaining within a range from 1 to 2% of prestressing force.

Various researches of CFCC tendons relaxation [5, 14] prove that their total relaxation after 100 hours can be estimated as 0.96–3.5% of prestressing force when the level of prestressing is relatively high (80% of their tensile strength). This means that prestressing force loss due to relaxation of FRP tendons is equal to the loss of conventional low relaxation steel strands, or it is even lower.

## 3. Ultimate limit state design

The ultimate limit state (ULS) design of structures prestressed with CFRP strands is connected with several conditions, which have to be taken into account. Firstly, in members prestressed with steel subjected to increasing loading an elastic behaviour can be observed before concrete's cracking, then increase of deflections and yielding of steel tendons occurs, and finally either tensile strength of the tendons is exceeded or concrete strains exceed maximum values. Structures which are prestressed with CFRP tendons behave differently, due to the fact that the CFRP has no possibility of yielding; strain-stress relation for composite materials is linear up to a sudden failure. That is why in the situation of a member loaded up to a failure, elastic deformations can be observed at the beginning, but later an increase of deflection is still linear before the member fails either by tendons rupture or by concrete crushing in compressive zone. In case of former situation, the failure is indeed sudden. Therefore it is accepted to design members prestressed with CFRP tendons in such a way to ensure a failure by concrete crushing, while it provides sufficient safety.

Both design procedures provided by ACI code [1] and ISIS guidelines [9] begin their analysis by estimating the way of failure of a member, i.e., calculating balanced reinforcement ratio and then checking whether provided reinforcement exceeds its value or not. The procedures for dimensioning members prestressed with CFRP reinforcement with rectangular or T-shaped cross sections with the compression zone height within the depth of a flange (quasi-rectangular) are provided in flowcharts below (Figs. 3 and 4).

A designed member has to fulfil also the requirements of relevant stresses at tensile and compressive fibres, which are presented in Table 2.

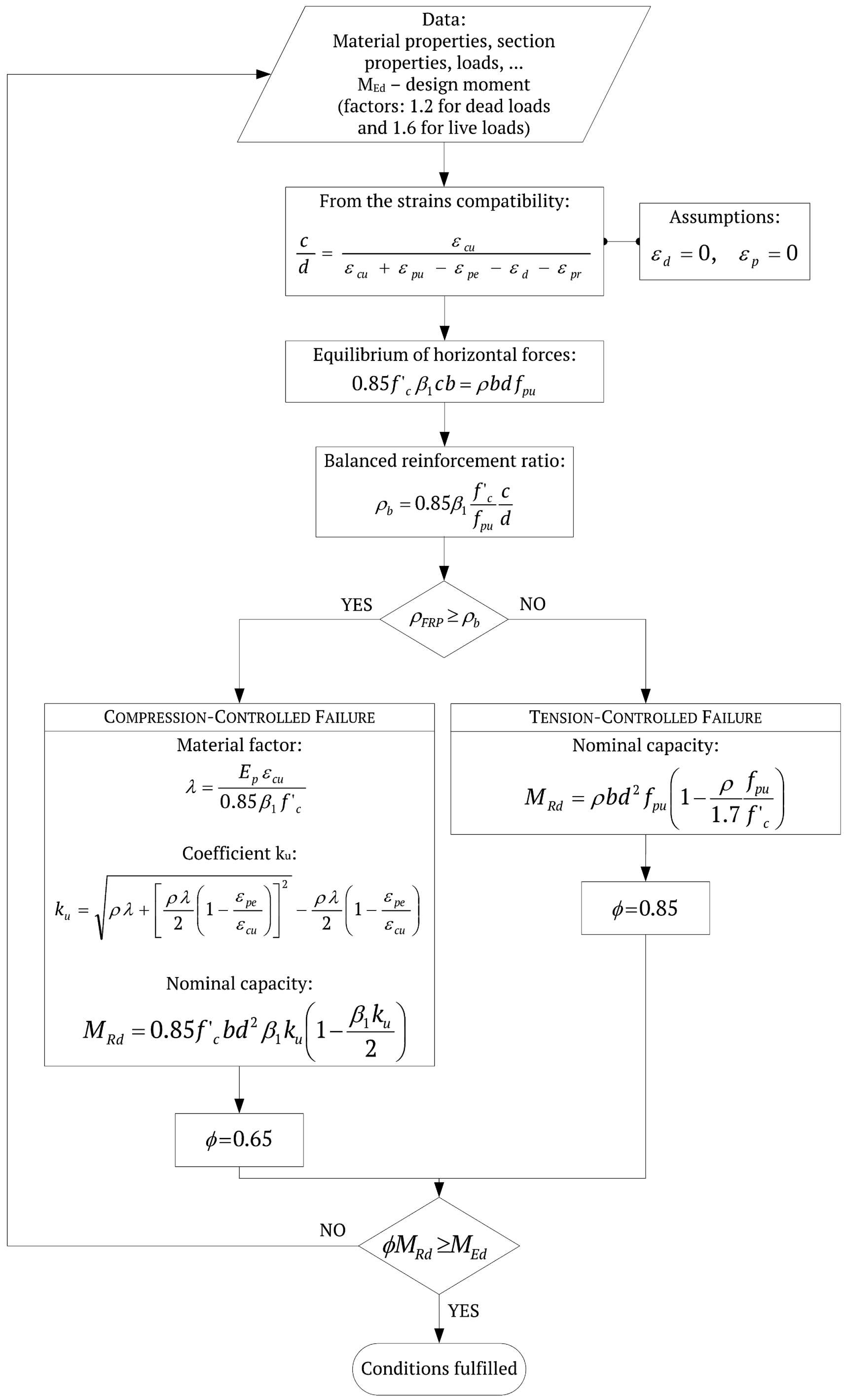


Fig. 3. ACI 440.4R-04 algorithm for rectangular or quasi-rectangular T-section.

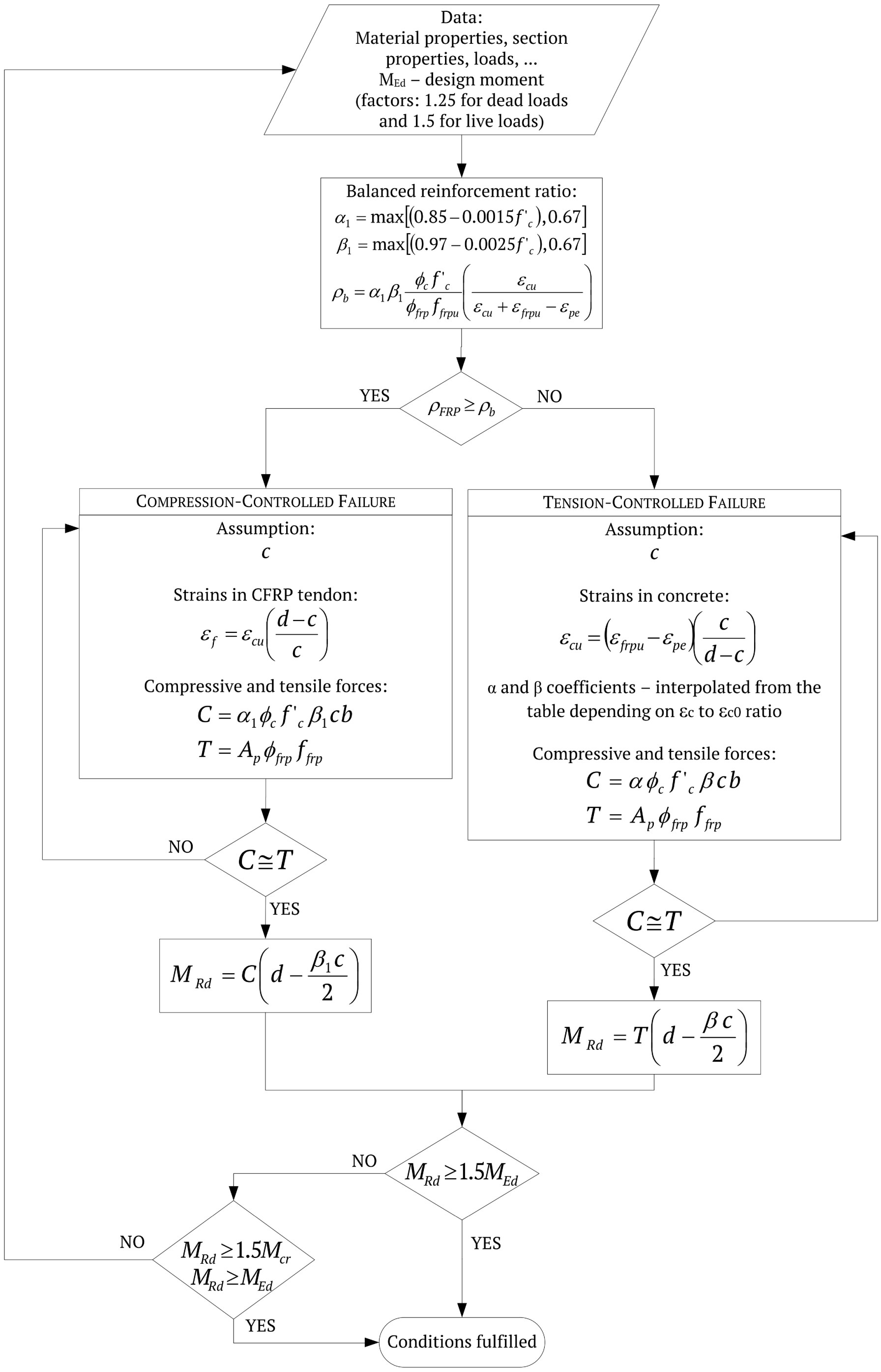


FIG. 4. The algorithm for rectangular or quasi-rectangular T-section from the ISIS Design Manual No. 5.

**Table 2**. Allowable fibre stresses.

| | | Canada [9] | America [1] |
|---|---|---|---|
| At jacking | pretensioned | $0.70\ f_{frpu}$ | $0.65\ f_{pu}$ |
| | post-tensioned | $0.70\ f_{frpu}$ | |
| At transfer | pretensioned | $0.65\ f_{frpu}/0.60\ f_{frpu}{}^{*}$ | $0.60\ f_{pu}$ |
| | post-tensioned | $0.65\ f_{frpu}$ | |

where $f_{frpu}$, $f_{pu}$ – the ultimate tendon tensile strength according to Canadian and American codes, respectively, * – the difference depends on the applied code – bridge design code allows $0.65\ f_{frpu}$, whereas the code for buildings $0.60\ f_{frpu}$.

## 4. Design example

The procedures presented in ACI [1] and ISIS [9] codes were applied to a one-span, simply supported I-beam of a cross section presented in Fig. 5, prestressed with seven CFCC tendons, each of which consisted of seven strands. The parameters of tendons are assumed as the ones used in [8], concrete compressive strength is equal to 40 MPa, other material parameters are calculated according to relevant Canadian or American standards, CAN/CSA A23.2-04 [3] and ACI 318R-11 [2], respectively. Dead loading value is calculated as a weight of

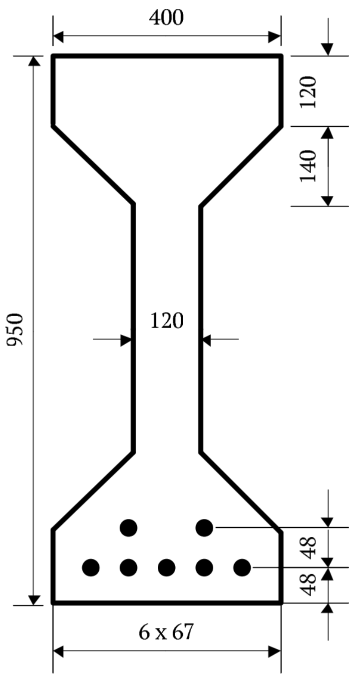


Fig. 5. I-beam cross section.

**Table 3**. Calculations for a design example according to ISIS and ACI guidelines.

| | | ISIS (2008) | ACI (2004) |
|---|---|---|---|
| Material properties | | | |
| Concrete compressive strength [MPa] | | 40 | |
| Concrete compressive strength at transfer [MPa] | | 30 | |
| Concrete elasticity modulus [GPa] | | 28.46 | 29.93 |
| Maximum concrete strains [–] | | 0.0035 | 0.0030 |
| CFRP tensile strength [MPa] | | 2558 | |
| CFRP elasticity modulus [GPa] | | 157 | |
| Maximum CFRP strains [–] | | 0.016 | |
| Cross section properties | | | |
| Total length [m] | | 12 | |
| CFRP tendons area (diameter = 15.2 mm) [mm$^2$] | | 115.5 | |
| Cross section area [cm$^2$] | | 2204 | |
| Modulus of inertia (including tendons) [m$^4$] | | 0.02506 | 0.02763 |
| Loadings | | | |
| Self-weight [kN/m] | | 5.51 | |
| Dead loads [kN/m] | | 12.5 | |
| Live loads [kN/m] | | 18 | |
| Characteristic value of moment [kNm] | | 648.18 | |
| Design value of moment ($M_{Ed}$) [kNm] | | 891.23 | 907.42 |
| Prestressing force and losses | | | |
| Initial prestressing force [kN]/[MPa] | | 827.1 kN/1023.2 MPa | |
| Loss from elastic shortening [MPa] | | 12.72 | 11.20 |
| Loss from creep of concrete [MPa] | | 34.26 | 49.27 |
| Loss from shrinkage of concrete [MPa] | | 26.00 | 25.62 |
| Loss from relaxation of tendons [MPa] | | 26.61 | 30.70 |
| Total losses [MPa]/[% of initial force] | | 99.68 (9.7%) | 116.79 (11.4%) |
| Prestressing force after losses [kN]/[MPa] | | 746.54 kN/ 923.52 MPa | 732.71 kN/ 906.41 MPa |
| Stresses at top and bottom edge of the beam [MPa] | | | |
| During transfer at support point | top | 2.553 | 1.967 |
| | bottom | −9.845 | −9.288 |
| During transfer in mid-span | top | 1.020 | 0.578 |
| | bottom | −8.364 | −7.944 |
| At service loading in mid-span | top | 10.047 | 9.452 |
| | bottom | −3.047 | −2.605 |

**Table 3**. [Cont.]

| ULS – flexural design | | |
|---|---|---|
| Balanced reinforcement ratio [–] | 0.0026 | 0.0037 |
| Provided reinforcement ratio [–] | 0.0040 | |
| Effective depth of compression zone [mm] | 260 | 277 |
| Strains in both layers of CFRP tendons [–] | 0.0145<br>0.0139 | 0.0160<br>0.0153 |
| Nominal capacity [kNm] | – | 2278.82 |
| Design capacity ($M_{Rd}$) [kNm] | 1170.05 | 1481.23 |
| $(M_{Ed})/(M_{Rd})$ [%] | 76.2 | 61.3 |
| Condition $M_{Rd} > 1.5M_{Ed}$ | 1170.05<1336.84 | (–) |
| $M_{cr}$ | 688.34 | (–) |
| Condition $M_{Rd} > 1.5M_{cr}$ | 1170.05>1032.51 | (–) |

10 cm thick reinforced concrete slab, assuming that I-beams are spaced every five metres, live load value is equal to 18 kN/m.

The beam is designed considering both ULS conditions and permissible stresses values (cf. Table 2). Final capacities obtained with ACI [1] and ISIS [9] differ considerably; however, their comparison is complex. ACI code applies only one, global factor to the nominal value of a capacity, and this factor causes high reduction when failure mode is assumed to be concrete crushing ($\Phi = 0.65$). Various coefficients used in Canadian guidelines separately for each material ($\Phi_c = 0.65$ for cast-in-place and precast concrete, $\Phi_{frp} = 0.85$ for CFRP tendons) lead to even lower results of final capacity. In conclusion, design value of capacity acquired with American standards [1] (1481.23 kNm) is higher in comparison to ISIS [9] value (1170.05 kNm), with a difference of 26.6%. Loading coefficients in both codes are also not equal and therefore design value of moment due to loading in ACI (907.42 kNm) is slightly higher than in ISIS (891.23 kNm), their difference is not considerable. Finally, comparing design values of ratios of moment caused by loadings to capacity of the girder gives results equal to 61.3% and 76.2% for ACI and ISIS, respectively. The beam designed according to ACI is obviously not efficient, but the aim of this example was to present how these algorithms vary.

## 5. Summary

Tendons made of composite materials are not to exchange conventional steel prestressing systems, but there are many areas, where their application will be justified and more efficient, such as external prestressing in difficult environmental conditions. Although structures prestressed with CFRP rods or CFCC tendons are already being built and many researches were conducted and intended to best recognize the new materials, there is still a lack of information on these materials for engineers and designers. Developing standards will allow not only to take these new unconventional solutions into consideration but also to introduce reliable prestressing systems into the market.

The topic of using FRP materials for prestressing structures can be found in the new Model Code 2010 [12], where the issues of their rheology parameters and relaxation of tendons are raised, which suggests that this subject is worth further researches and composite materials possess many characteristics desired in prestressing structures. The study areas such as proper anchorages, protection from high temperatures and improving fire resistance as well as long-term phenomena and many others still remain important in further studies.

## Acknowledgment

Paper presented at the 1st National Student's Conference BUDMIKA 2014, Poznań, April 23–25, 2014.

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*Received November 7, 2014; accepted version June 5, 2015.*