MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 21. Year 2019 ISSN 1506-218X 1505-1514

Bending Moment of the Waste Fine Aggregate Concrete Beams

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1. Introduction

The strength of fiber reinforced concrete meant as load carrying capacity, resistance to cracking or limiting magnitude of strain and shifting is a decisive factor on its suitability in concrete structures (Głodkowska & Ziarkiewicz, 2018), (Błaszczyński & Przybylska-Fałek, 2015). The fibres cause, in every case, significant increase of energy needed to destroy the element for any type of loading (Sucharda, Pająk, Ponikiewski, & Konecny, 2017), (Sadowska-Buraczewska, 2016), (Domski, 2015), (Seitl, Keršner, Bílek, & Knésl, 2010), (Kormeling, Reinhardt, & Shah, 1980). The strength increases with the number and performance of steel fibres (Maidl, 1995), (Meda, Minelli, & Plizzari, 2012), (Pająk & Kühn, 2016), (Domski & Głodkowska, 2017). The highest influence of steel fibres is obtained in the case of bending, which depends on, among other things, arrangement of the fibres within the cross-section. The fibres located in the element tension zone, particularly at the element edge, are used most efficiently (Yazıcı, İnan, & Tabak, 2007), (Ponikiewski, Katzer, Bugdol, & Rudzki, 2014), (Sadowska-Buraczewska & Skrzypczak, 2019).

The method of calculation of the fiber reinforced concrete beams load carrying capacity depends on the adopted distribution of stress-strain in the compressed and stretched zones. Authors of the article (Henager & Doherty, 1976) adopted in the seventies a simplified model of stress pattern and linear variability of strain at beam's height. The method was accepted for application by the American Concrete Institute (ACI-544.4R-88, 1994) at the maximum value of compressive strain fixed by (Henager & Doherty, 1976) at 0.003. Pearlman, Swamy and Al-Ta`an, Hassoun and Sahebjam, Lok and Xiao proposed different value of the maximum strain in the compressed zone making it dependent on, for example, amount of the fibres applied. There are also some other methods of calculation of load carrying capacity of fiber reinforced concrete beams proposed by, among others, (Swamy & Al-Ta`an, 1981) (Narayanan & Kareem-Palanjian, 1986), (Craig, Decker, Dombrowski, Laurencelle, & Federovich, 1987), (Lim, Paramasivam, & Lee, 1987), (Ezeldin & Shiah, 1995), (Imam, Vandewalle, & Mortelmans, 1995), (RILEM TC 162-TDF, 2003), (Padmarajaiah & Ramaswamy, 2004), (fib Bulletin 55, 2010) but they are not included within this paper.

The laboratory test results for the critical load carrying condition of beam elements made of plain concrete and waste fine aggregate concrete containing steel fibres 50/0.80 and 30/0.55 (Zarzycki, Katzer, & Domski, 2017) have been shown in this paper. The destruction moments obtained during the experiments were compared with analytical values acquired by application of some selected calculation methods.

2. Description of experiments

The experiments were carried out in six beams dimensioned 150×200×3300 mm. Sixteen beams were made of waste fine aggregate concrete and two of plain concrete. The beams were loaded with two concentrated forces applied at 1/3 beam span. The beam test loading diagram is shown in Fig. 1.

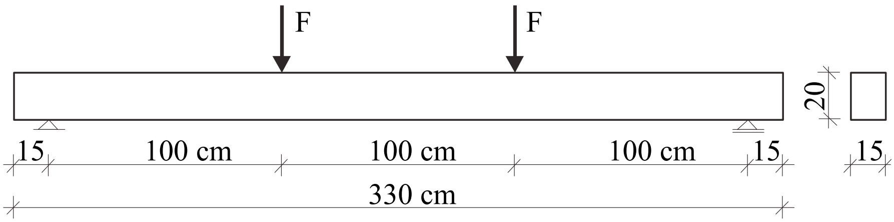

Fig. 1. Beam geometry and loading arrangement diagram

The magnitude of the loading applied was controlled by beam support reaction reading using SAD 256 data acquisition computer system. The system was used, in the presented study, also for measurement of beam tensioned reinforcement strain. It was measured with foil strain gauge glued (before concrete pouring) to two tensioned rods. TFs-5/120 foil strain gauges (120.3 Ω ± 0.2% resistance and gauge factor k = 2.15 ± 0.5%) connected to SAD 256 system via the so-called Wheatstone's bridge have been applied. The longitudinal beam reinforcement was made of ribbed steel (34GS grade) dia. 10, 12 and 14 mm, whereas the transversal reinforcement was made of smooth steel (St3SX-b grade) dia. 4.5 mm. Only ribbed steel was tested for its mechanical properties. The yield point within 424-454 MPa range, tensile strength from 695 MPa to 714 MPa and modulus of elasticity from 220 GPa to 223 GPa were obtained. It appears from the tests performed that ribbed steel used in this study featured a very distinct yield point.

The marking, beam characteristics and strength features of concrete applied are shown in Table 1. The tensile strength while in splitting ($f_{ct,sp}$) experiments were carried out on 150 mm cubes. The cylindrical compressive strength (f_c) and modulus of elasticity (E_c) were established for cylindrical samples featuring diameter of 150 mm and height of 300 mm, received by cutting samples featuring height of 450 mm on both ends.

Table 1. Beam characteristics and associated test results

<table>
<tr><th rowspan="2">Beam marking</th><th rowspan="2">Fibres l/d_f [mm/mm]</th><th colspan="2">Longitudinal and transversal reinforcement</th><th colspan="3">Concrete mechanical features</th></tr>
<tr><th>Top rods / bottom rods</th><th>Stirrups and their spacing</th><th>$f_{ct,sp}$ [MPa]</th><th>f_c [MPa]</th><th>E_c [GPa]</th></tr>
<tr><td>B–1, B–2</td><td rowspan="3">50/0.80</td><td>2#8 / 3#10</td><td rowspan="7">ϕ 4.5 mm at 130 mm</td><td rowspan="3">3.57</td><td rowspan="3">50.2</td><td rowspan="3">34.2</td></tr>
<tr><td>C–1, C–2</td><td>2#8 / 3#12</td></tr>
<tr><td>G–1, G–2</td><td>2#8 / 3#14</td></tr>
<tr><td>H–1, H–2</td><td rowspan="3">30/0.55</td><td>2#8 / 3#14</td><td rowspan="3">2.89</td><td rowspan="3">38.4</td><td rowspan="3">26.0</td></tr>
<tr><td>I–1, I–2</td><td>2#8 / 3#12</td></tr>
<tr><td>J–1, J–2</td><td>2#8 / 3#10</td></tr>
<tr><td>F–1, F–2</td><td>–</td><td>2#8 / 3#10</td><td>3.82</td><td>51.9</td><td>33.4</td></tr>
</table>

To produce the B, C, G, H, I and J series beams natural fraction aggregate (0-4) mm, being the residue of aggregate hydroclasification in the gravel pit in Sępólno Wielkie (West Pomerania) was used. 30/0.55 or 50/0.80 hooked steel fibres (Zarzycki, Katzer, & Domski, 2017) featuring slenderness ratio 54.5 and 62.5 respectively were added alternately to the fine aggregate concrete mix. Plain commercial concrete, class C35/45, produced in „Dźwigbet" in Koszalin was used to produce the F series beams. The waste fine aggregate concrete containing steel fibres mix compositions (Domski, 2016) are shown in Table 2.

Table 2. Fine aggregate concrete compositions [kg/m^3]

Mix components (Domski, 2016)	H, I, J series	B, C, G series
Waste sand (0-4 mm)	1855	1835
CEM II/B-V 32.5 R cement	378	374
Water	140	150
FM 34 superplasticiser	3.83	3.78
Steel fibres	34	33

3. Test results and their analysis

The value of the moment at which it was assumed that the beam was destroyed (Fig. 2), was being established from the reinforcement steel strain and bending moment relationship graph. The moment magnitude at which the reinforcement steel "flew", registered by an electric resistance wire strain gauge glued to the reinforcing rods, was being taken form the graph. All the beams under review were destroyed due to arrival at the yield point of the stretched steel reinforcement.

Fig. 2. View of the damaged beam

Figure 3 shows examples of the bending moment and reinforcing steel strain relationship graphs. The horizontal line (at strain value approx. 0.2 percent) at the graph (Fig. 3) shows the reinforcing steel yield point calculated on the basis of the accompanying experiments assuming the linear relationship of σ-ε. All the analysed beams were destroyed at the higher than calculated level of steel strain. Also strain values in beam lateral surfaces were being determined for the load at which the yield point was being reached using linear transducer gauge measurements.

According to (Henager & Doherty, 1976) the location of the neutral axis for plain concrete doesn't change much with increase of the load i.e. between 0.42 and 1.0 of the destructive force value the neutral axis stays practically at the same position whereas in the steel fibre containing beams the location of the neutral axis shifts along with increase of the load towards the compressed reinforcement. The above relationship for fine aggregate concrete was recorded in the presented own research but the phenomenon described by Henager and Doherty for plain concrete was not observed during said research work. Figure 4 shows examples of graphs of strain occurring at beam height in the middle of its span. No significant difference in graph shape and in strain values between plain concrete and fine aggregate concrete was established.

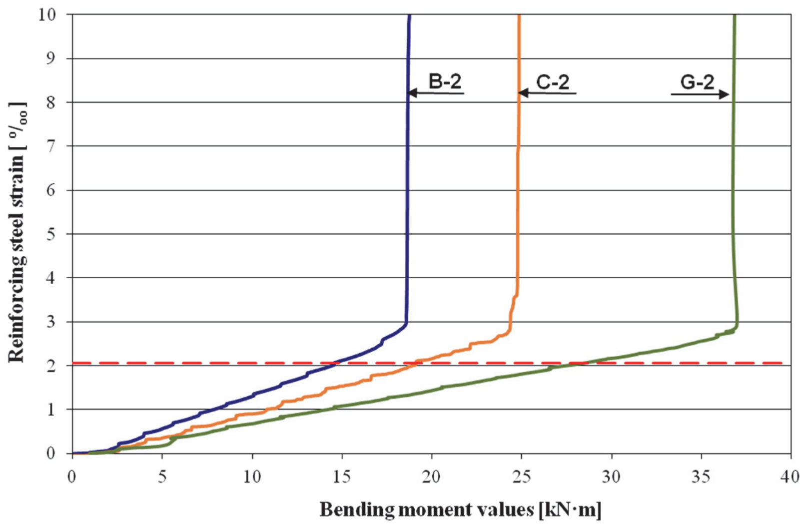

Fig. 3. The bending moment in function of the reinforcing steel strain for selected beams

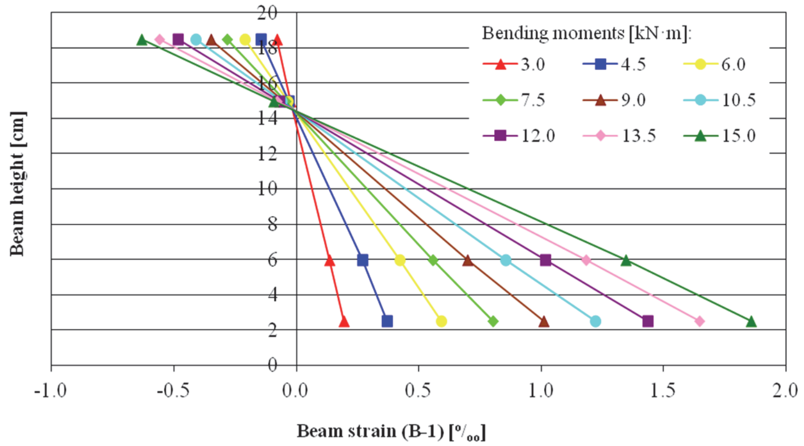

Fig. 4. Lateral strain of beam surface (B-1)

The results of the load carrying capacity of fine aggregate concrete beams were compared with the values calculated on the grounds of American Concrete Institute method (ACI-544.4R-88, 1994), the diagrams of which are shown in Figure 5.

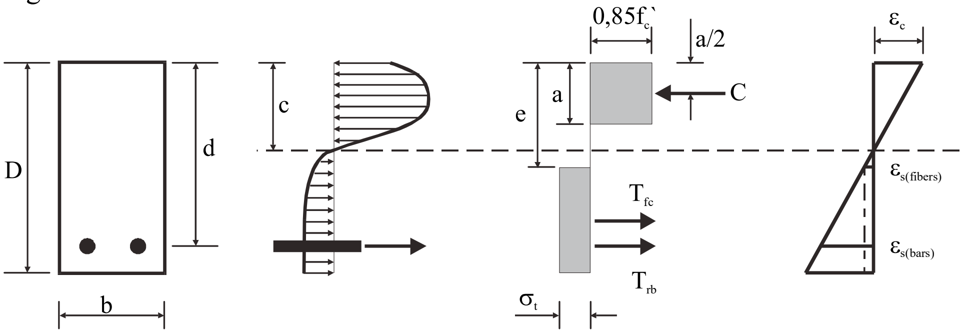

Fig. 5. The diagram of calculation of the carrying capacity of beams containing steel fibres according to (Henager & Doherty, 1976)

Assuming the distribution of stress as in Fig. 5 the load carrying capacity of the cross-section can be calculated from equation (1) (notations as those used in Fig. 5).

$$M_t = A_s f_y \left(d - \frac{a}{2} \right) + \sigma_t b (D - e) \left(\frac{D}{2} + \frac{e}{2} - \frac{a}{2} \right) \tag{1}$$

The distance "e" shall be determined from Fig. 5 assuming that the maximum strain of the outermost compressed fibre (ε_c) is 0.003:

$$e = \frac{\left(\varepsilon_{s(fibres)} + 0.003 \right) \cdot c}{0.003} \tag{2}$$

where:

$$\varepsilon_{s(fibres)} = \frac{\sigma_f}{E_s} = \frac{2 \tau_d F_{be} l}{d_f E_s} \tag{3}$$

whereas "σ_t" strain is, according to formula (4):

$$\sigma_t = 0.00772 \frac{l}{d_f} \rho_f F_{be} \tag{4}$$

In the above formula ρ_f means the steel fibre content by volume (percentage) whereas F_{be} is a factor which depends on fibre shape taking values from 1.0 for straight fibres to 1.2 for hooked ones. Where l is the length, d_f is the diameter of the fibres and τ_d is the dynamic bond stress between the fiber and the matrix.

The calculated and measured breaking moment values compared with results obtained by other authors are shown in Table 3 and Figure 6.

Table 3. Load carrying capacities of the tested beams

Beam marking	Breaking moments		M_C / M_T
	Tested M_T [kN·m]	Calculated M_C [kN·m]	
B–1; B–2	18.39; 18.82	18.45*	1.00; 0.98
C–1; C–2	24.70; 24.40	24.18*	0.98; 0.99
G–1; G–2	35.94; 36.94	33.72*	0.94; 0,91
H–1; H–2	36.45; 34,30	31.92*	0.88; 0.93
I–1; I–2	23.84; 23.78	23.78*	1.00; 1.00
J–1; J–2	18.52; 17.44	18.08*	0.98; 1.04
F–1; F–2	17.48; 17.62	16.07**	0.92; 0.91
* – according to (Henager & Doherty, 1976) ** – as per Eurocode 2 (EN-1992-1-1, 2008)			

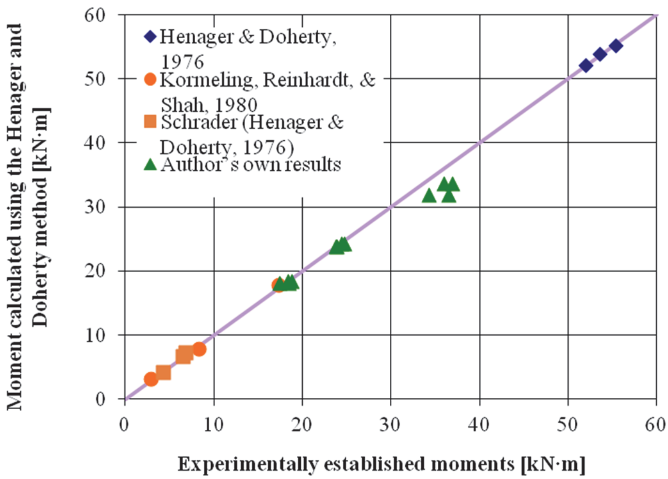

Fig. 6. The diagram of calculation of the carrying capacity of beams containing steel fibres according to (Henager & Doherty, 1976)

It appears from the above comparison that the method of calculation of the load carrying capacity of beams containing steel fibres applied by American Concrete Institute (ACI-544.4R-88, 1994) reflects well the test results for the wide scope of the tested elements. The mean differences between the calculated moment value and that obtained in tests do not exceed in the described experiments 3.1%. The analysis of beams made of plain concrete (F) showed that the breaking moment values calculated by application of the method used in the Eurocode 2 (EN-1992-1-1, 2008) are on average lower by 8.4% than those obtained in the tests.

4. Summary

The results of load carrying capacity of the tested beams containing steel fibres and the values calculated by application of the method proposed by (Henager & Doherty, 1976) show high correlation. The achieved spread (3.1%) falls well within the test spread obtained by the method authors i.e. from 2.8% to 6.3%. Such good consistency of results indicates that the calculation model applied was correct, however, it should be borne in mind that the model does not take into account the reinforcement within the compressed zone. The values of above method must be underlined here i.e. taking into account the influence of steel fibres within the cross-section stretched zone onto element load carrying capacity.

Having analysed the breaking moments achieved for beams containing steel fibres (B and J) and plain concrete beams (F) one can see that the load carrying capacity of the former is on average higher by 2.4% for beams (J) containing 30/0.55 steel fibres and 5.7% for beams (B) containing 50/0.80 fibres and the applied content of steel fibres by volume was: 0.43% and 0.42% respectively. At higher level of fibre reinforcement the load carrying capacity can increase even by 26% (Henager & Doherty, 1976).

The method indicated in the Eurocode 2 (EN-1992-1-1, 2008) can also be applied for calculation of the load carrying capacity of the waste fine aggregate concrete beams containing steel fibres but this method gives too low values for the breaking moments. The difference for the described experiments was on average 11.9% for the beams (J) containing 30/0.55 steel fibres and 15.8% for the beams (B) containing 50/0.80 steel fibres respectively.

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Abstract

This report presents the results of laboratory experiments of bending moment for fourteen concrete beams with steel bars. Twelve of the beams were made of waste fine aggregate concrete containing steel fibres: six with steel fibres 30/0.55 and six with steel fibres 50/0.80. The next two beams were made of plain concrete. The results of the experiments were compared with theoretical calculations based on a Eurocode 2 and also with the method suggested by Henager and Doherty.

Keywords:
waste sand, fine aggregate, composite, steel fibres

Moment zginający belek żelbetowych z drobnego kruszywa odpadowego

Streszczenie

Artykuł przedstawia wyniki laboratoryjnych badań momentu zginającego czternastu belek żelbetowych. Dwanaście z nich wykonano na bazie piasku odpadowego wzbogaconego włóknami stalowymi tj.: sześć z włóknami 30/0.55 i sześć z włóknami 50/0.80. Pozostałe dwie belki wykonano z betonu zwykłego. Wyniki badań eksperymentalnych zostały porównane z obliczeniami przeprowadzonymi na podstawie Eurocode 2 i metody zaproponowanej przez Henager i Doherty.

Słowa kluczowe:
piasek odpadowy, drobne kruszywo, kompozyt, włókna stalowe