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Research paper

Comparative analysis of the BFRP and steel reinforcement bars under fire conditions

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Abstract: The FRP reinforcement gained importance due to high tensile strength, high durability and ecological friendliness [1–7]. Its usefulness as the internal or Near Surface Mounted reinforcement in bent concrete elements has already been proven. Though, in terms of the compressive behaviour of the bars and concrete elements incorporating them, there are still few experimental and numerical considerations, especially when high temperatures are considered. This article contains further considerations on the performance of concrete columns with BFRP main reinforcement in fire resistance tests on the basis of previously presented authors' numerical analyses. Comparative analysis in terms of temperatures, deformations and stresses of concrete columns with BFRP and steel main reinforcement in fire resistance tests is presented by the example of two columns, for which also experimental investigations were performed. Also, a comparative analysis of stress-strain relations for BFRP, steel and concrete at temperatures up to 600°C is presented. It can be concluded that BFRP bars' properties are strongly different when compressive and tensile performance is considered, especially at elevated temperatures. Tensile strength was higher for BFRP than steel at room temperature, but along with temperature growth, it came the other way (at around 600°C). The compressive strength of the BFRP bars was higher than the value for concrete, but only for temperatures lower than 200°C.

Keywords: Basalt Fibre Reinforced Polymer, non-metallic reinforcement, fire, temperature, concrete column

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1. Introduction

The FRP reinforcement gained popularity due to high tensile strength, high durability and ecological friendliness. Its usefulness as the internal or Near Surface Mounted reinforcement in bent concrete elements has already been proven; fire safety considerations are also available in that matter [8–11]. Though, in terms of the compressive behaviour of the bars and concrete elements incorporating them, experimental and numerical considerations are still rather scary, especially when high temperatures are considered.

This article contains further considerations on the performance of concrete columns with BFRP main reinforcement in fire resistance tests on the basis of previously presented authors' numerical analyses [12]. Comparative analysis in terms of temperatures, deformations and stresses of concrete columns with BFRP and steel main reinforcement in fire resistance tests is presented on the example of two columns, for which also experimental investigations were performed [12, 13]. Material tests' results (e.g. Dynamic Mechanical Analysis, Thermogravimetric Analysis, compressive/tensile mechanical tests at room and high temperatures) on the BFRP bars have been discussed in [12, 14].

2. Materials and specimens

Table 1 presents used reduction ratios for compressive strength and elasticity modulus at compression for BFRP, along with temperature growth, determined on the basis of own studies [12, 14]. The assumptions in terms of material properties for concrete, BFRP bars and steel bars, as well as parameters of analysed columns, are presented in Table 2.

Table 1. Reduction ratios along with temperature growth – compressive strength and elasticity modulus at compression, BFRP bars [12, 14]

Temperature [°C]	Reduction of compressive strength [%]	Reduction of elasticity modulus [%]
20	0	0
50	13	4
100	81	42
200	93	52

Table 2. Assumptions for numerical modelling [12]

<table>
<tr><th>Material</th><th>Properties</th><th>Columns with steel main reinforcement</th><th>Columns with BFRP main reinforcement</th></tr>
<tr><td rowspan="10">Concrete</td><td>Compressive strength at room temperature</td><td>73.7 MPa[1]</td><td>32.0 MPa[1]</td></tr>
<tr><td>$\sigma - \varepsilon_{\mathrm{mech}}$ dependencies in compression at high temperatures</td><td colspan="2">As per European standards [15]</td></tr>
<tr><td>Tensile strength at room temperature</td><td colspan="2">As per European standards [16]</td></tr>
<tr><td>$\sigma - \varepsilon_{\mathrm{mech}}$ dependencies in tension at high temperatures</td><td colspan="2">As per European standards [15]</td></tr>
<tr><td>CDP parameters</td><td colspan="2">dilatation angle: 36, eccentricity: 0.1, f_{b0}/f_{c0}:1.16, κ: 0.667 and viscosity parameter: 5E-05 [17][3]</td></tr>
<tr><td>Poisson's ratio</td><td colspan="2">0.2[3]</td></tr>
<tr><td>Density</td><td colspan="2">2400 kg/m^3 [1, 2]</td></tr>
<tr><td>Changes in density at high temperatures</td><td colspan="2">As per European standards [15]</td></tr>
<tr><td>Specific heat</td><td colspan="2">As per European standards [15] (for 3% moisture content)</td></tr>
<tr><td>Thermal conductivity</td><td colspan="2">As per European standards [15] (medium value from the lower and upper curve)</td></tr>
<tr><td rowspan="7">Steel</td><td>Yield strength of stirrups</td><td>750 MPa[1]</td><td>500 MPa[5]</td></tr>
<tr><td>Yield strength of the main bars</td><td>446 MPa[1]</td><td>Not applicable</td></tr>
<tr><td>$\sigma - \varepsilon_{\mathrm{mech}}$ dependencies at high temperatures</td><td colspan="2">As per European standards [15]</td></tr>
<tr><td>Poisson's ratio</td><td colspan="2">0.3</td></tr>
<tr><td>Density</td><td colspan="2">7850 kg/m^3</td></tr>
<tr><td>Specific heat</td><td colspan="2">420 kJ/(kg·K) [3]</td></tr>
<tr><td>Thermal conductivity</td><td colspan="2">45 W/(m·K) [3]</td></tr>
<tr><td rowspan="7">BFRP</td><td>Compressive strength at room temperature</td><td rowspan="7">Not applicable</td><td>500 MPa[1]</td></tr>
<tr><td>Modulus of elasticity at room temperature in compression</td><td>35 GPa[1]</td></tr>
<tr><td>Reduction of strength and elasticity modulus in compression at high temperatures</td><td>Tab. 1</td></tr>
<tr><td>Poisson's ratio</td><td>0.25 [18–20,21[3]]</td></tr>
<tr><td>Density</td><td>2000 kg/m^3 [1]</td></tr>
<tr><td>Specific heat</td><td>1000 J/(kg·°C)[1]</td></tr>
<tr><td>Thermal conductivity</td><td>0.5 W/(m·K)[1]</td></tr>
</table>

Continued on next page

Table 2 – *Continued from previous page*

Material	Properties	Columns with steel main reinforcement	Columns with BFRP main reinforcement
Columns	Columns' height	2900 mm	3700 mm
	Cross section	300 mm in diameter	300 mm in diameter
	Bars' diameter and quantity	8#16	8#12
	Stirrups' spacing	4 cm (in upper and lower parts) or 16 cm (the rest)	4 cm (in upper and lower parts) or 8 cm (the rest)

[1] experimentally determined values [12–14]; [2] from European standards [15] or [16]; [3] on the basis of literature data; [4] only for room temperature; [5] as per grade 500 rebar

3. Methods

3.1. Stress-strain relations analysis

Firstly, the comparative analysis was performed for stress-strain relations of the three materials (concrete in compression, BFRP in tension/compression and steel) for various temperature ranges.

Own experiments [12, 14] were used to assume compressive performance at room and high temperatures of the BFRP and tensile performance at room temperature. Reduction of tensile strength and elasticity modulus along with the temperature growth was assumed on the basis of literature data [22]. The FRP bars with similar composition were chosen in that case (same matrix type: epoxy and similar percentage volume of fibres).

Assumptions for the concrete and steel were according to the European standard [15]. The concrete compressive strength at room temperature was equal to 35 MPa because the column analysed in the next section was made of similar concrete. Similarly, the yield strength of steel was assumed as 446 MPa, as the main reinforcement of the column with steel main bars in the next section was made of such steel.

3.2. Columns with BFRP/steel main reinforcement – comparative analysis

The analyses presented herein are the continuation of studies presented in [12]. The general assumptions for numerical modelling are as follows.

The mesh assemblies consisted of:

- two rigid bodies (upper and lower, r3d4 mesh elements) with reference points, at which boundary conditions for deformations were identified (lower: no rotation and movement, upper: enabled movement at Y axis and rotation against X axis);
- three concrete parts (modelled with 15 mm cubic c3d8t coupled temperature-displacement finite elements), connected with each other by "tie" constraint, one of

which was heated according to standard curve [23] (lengths of heated part: 3000 mm for the columns with BFRP main reinforcement and 1800 mm for concrete columns with main steel reinforcement);

- reinforcement bars (modelled either by truss t3d2t – columns with steel main reinforcement or 3D c3d8t – columns with BFRP main reinforcement, coupled temperature-displacement finite elements) – columns with main steel reinforcement as S2 column presented in [13] and columns as per Fig. 1b.

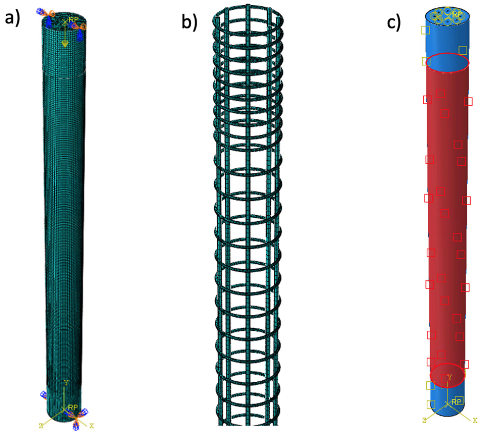

Fig. 1. Columns' numerical representation in Abaqus – specimen with BFRP main reinforcement, a) concrete mesh (c3d8t finite elements, 15 mm), b) reinforcement bars (c3d8t finite elements, 15 mm), c) heated part

Calculations were performed in two steps. The pressure was given through the rigid body in the first step (static, general). Then, the heating was modelled in the second step (coupled temp–displacement–transient) with the use of surface radiation interaction with ambient temperature amplitude created in the form, in which every 300 seconds increment, there is attributed a value corresponding to temperature according to [23]. The emissivity coefficient was assumed as 0.85 [24–26].

4. Results and discussion

4.1. Stress-strain relations' analysis

The most beneficial advantage for the FRP bars is their high tensile strength (two times higher than yield strength for steel – Fig. 2), while compressive strength is comparable to steel at room temperature.

Along with temperature growth up to 100°C or 200°C, the tensile strength of the BFRP is still much higher than the yield strength for steel, but compressive strength is almost negligible compared to steel (Figs. 3 and 4).

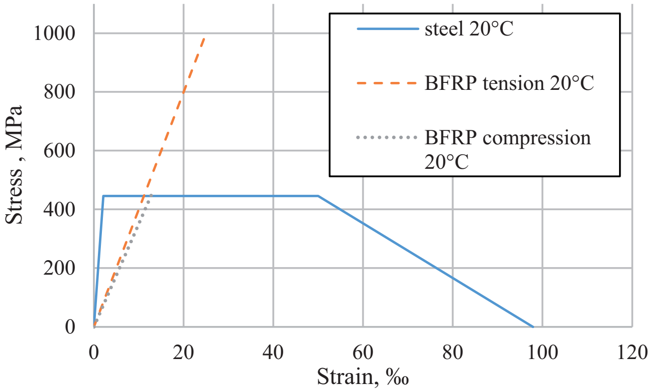

Fig. 2. Comparison between stress-strain relationships for steel (European standard [15]) and BFRP bars during compression (own experiments [13,14]) or tension (own experiments [12,14] and literature data [22]): 20°C

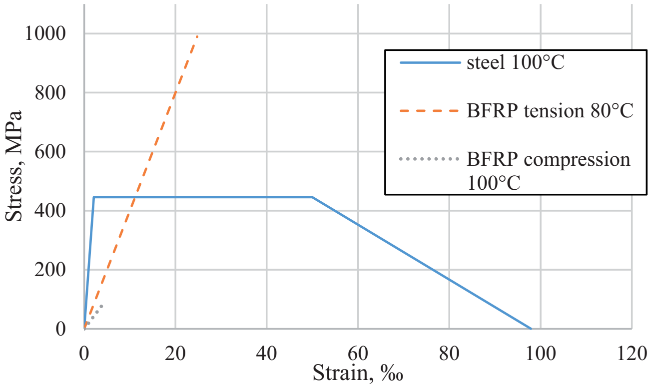

Fig. 3. Comparison between stress-strain relationships for steel (European standard [15]) and BFRP bars during compression (own experiments [12,14]) or tension (own experiments [12,14] and literature data [22]): 80–100°C

However, the BFRP in tension still has a quite high tensile strength, which is higher than maximum stresses for steel at 300°C and at even 600°C (Fig. 5 and Fig. 6).

As previously mentioned, BFRP in compression has comparable compressive strength to steel yield strength at room temperature (Fig. 2) and is significantly lower at even slightly elevated temperatures (up to 100–200°C – Figs. 3 and 4). When comparing BFRP to concrete, it has much higher compressive strength at room temperature (Fig. 7), but at 200°C, it decreases, and the influence of the bars might not be noticeable in compression at and over that temperature. Moreover, it may have a negative influence by weakening the concrete due to the possible ignition and burning of FRP bars, which then cause the internal heating of the concrete (Fig. 10a).

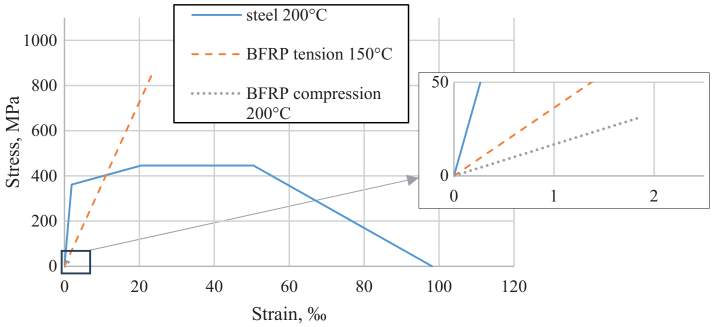

Fig. 4. Comparison between stress-strain relationships for steel (European standard [15]) and BFRP bars during compression (own experiments [12, 14]) or tension (own experiments [12, 14] and literature data [22]): 150–200°C

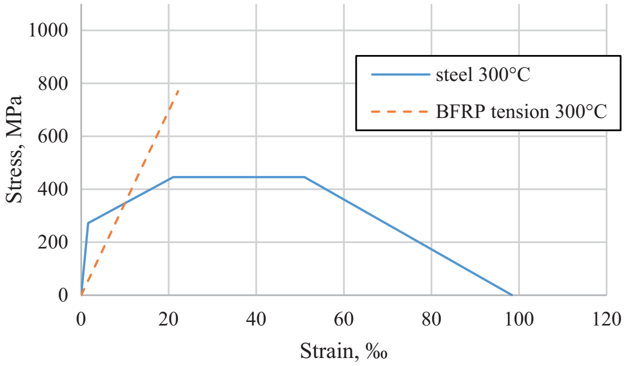

Fig. 5. Comparison between stress-strain relationships for steel (European standard [15]) and BFRP bars during tension (own experiments [12, 14] and literature data [22]): 300°C

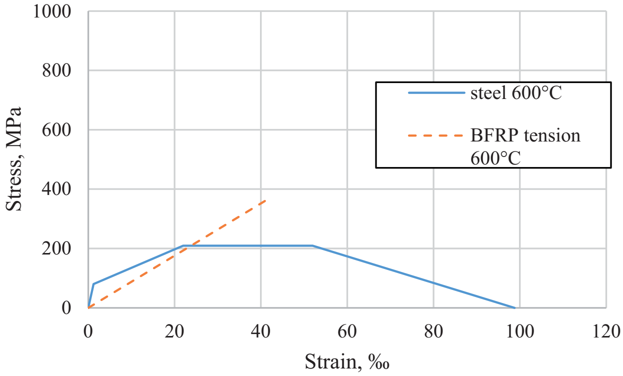

Fig. 6. Comparison between stress-strain relationships for steel (European standard [15]) and BFRP bars during tension (own experiments [12, 14] and literature data [22]): 600°C

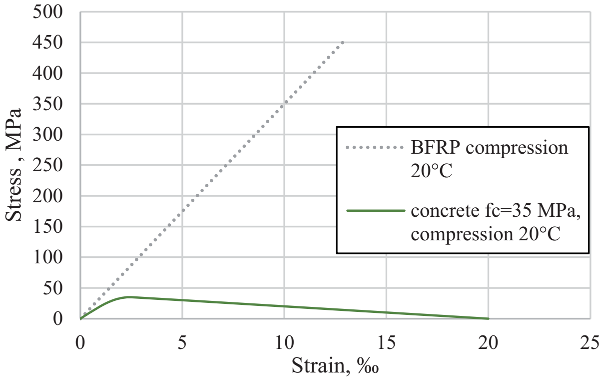

Fig. 7. Comparison between stress-strain relationships for concrete (European standard [15]) and BFRP bars during compression (own experiments [12, 14]): 20°C

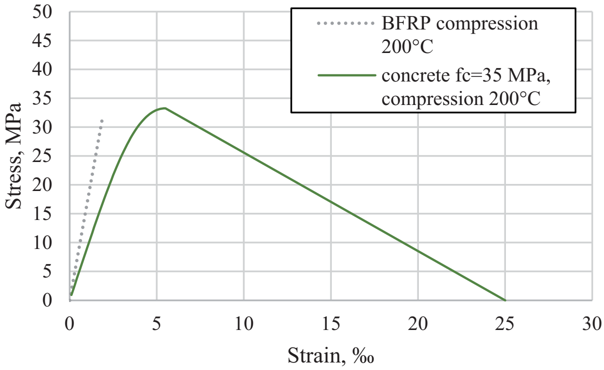

Fig. 8. Comparison between stress-strain relationships for concrete (European standard [15]) and BFRP bars during compression (own experiments [12, 14]): 200°C

4.2. Columns with BFRP/steel main reinforcement – comparative analysis

Firstly, deformations during failure, which are significantly different for each column, are analysed (Fig. 9). For the steel-reinforced column (Fig. 9b), the formation of the failure area is restricted to a small array, where the plastic hinge started to create. On the other hand, the BFRP-reinforced column (Fig. 9a) demonstrated rapid buckling deformation at some point in the simulation, followed by specimens' failure. This may be due to the low elasticity of the main BFRP bars compared to the stiff steel main bars in other columns.

This is also in line with the failure type of these elements in the experimental fire resistance test (column S2 in [13] and own experiment – Fig. 10). Also, referring to the experimental behaviour of the columns, a significant difference was that in the case of a column with BFRP main reinforcement flames started to appear coming outside of the concrete column (Fig. 10a).

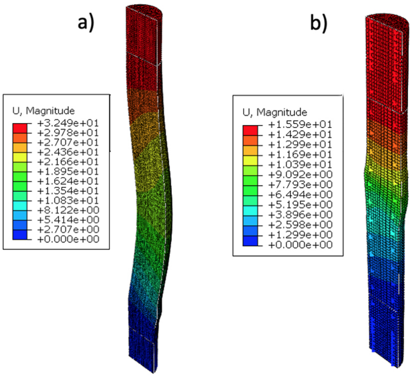

Fig. 9. Deformations' map at columns' failure: a) column with BFRP main reinforcement; b) column with steel reinforcement

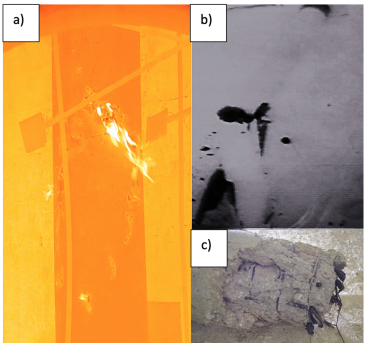

Fig. 10. Fire resistance tests of a concrete column with BFRP internal reinforcement: a) flames coming outside of the specimen, b) failure mechanism; c) concrete column after the test

Then, temperature distributions are shown in Figs. 11 and 12, which are comparable. The maximum value of temperature in bars (614.3°C and 649.3°C) differs mostly because of the differences in time of failure in numerical simulation (168 min and 170 min) and various concrete cover thicknesses (50 mm and 40 mm).

Despite comparable temperature distributions, stresses in the main bars differ significantly (Fig. 13). As the stresses in BFRP bars are negligible (36 MPa, and might be even lower, or the bars might be completely burnt out or destroyed in a real experiment), the steel bars in most exploited areas still retained considerable level of stresses (204 MPa).

The maximum stresses in steel stirrups in both cases remained high (Fig. 14). They were also about two times higher for the BFRP-reinforced element (258.2 MPa) than the steel-reinforced one (114.2 MPa).

In the case of concrete, the maximum stresses in a concrete core are easily visible in the unheated internal zone of the column, and their values (29.1 MPa for a column with BFRP main reinforcement bars and 69.18 MPa for a column with steel main reinforcement) are close to the compressive strength of concrete at room temperature (32 MPa and 73.7 MPa, respectively – Fig. 15).

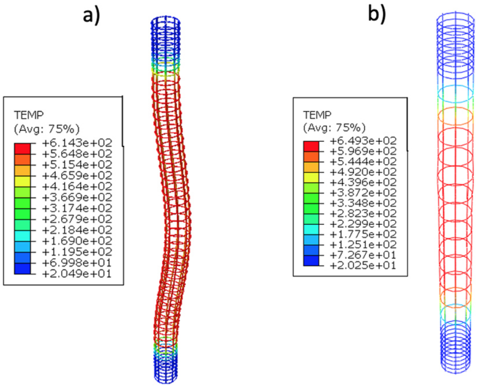

Fig. 11. Temperatures in the reinforcement at columns' failure: a) column with BFRP main reinforcement; b) column with steel reinforcement

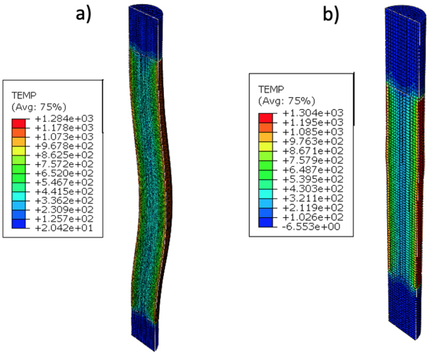

Fig. 12. Temperatures in the concrete at columns' failure: a) column with BFRP main reinforcement; b) column with steel reinforcement

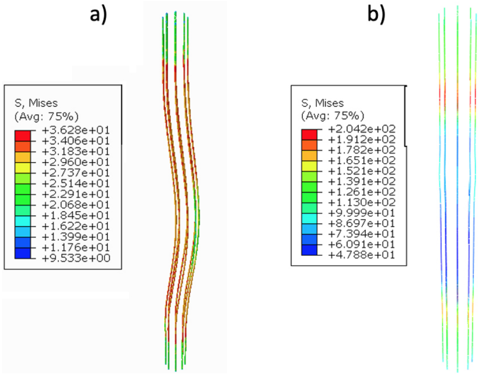

Fig. 13. Stresses' map in main bars a) column with BFRP main reinforcement; b) column with steel reinforcement

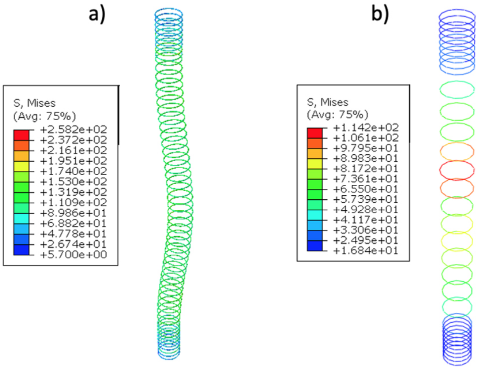

Fig. 14. Stresses' map in transverse bars a) column with BFRP main reinforcement; b) column with steel reinforcement

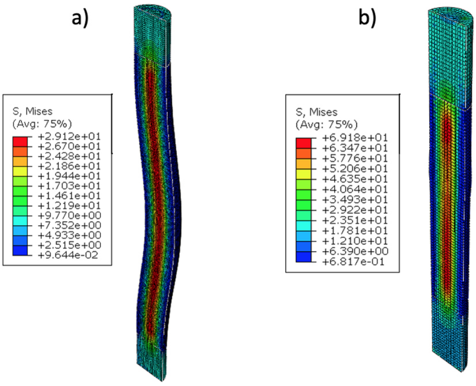

Fig. 15. Stresses' map in concrete a) column with BFRP main reinforcement; b) column with steel reinforcement

5. Conclusions

The following conclusions can be drawn from the presented study:

1. BFRP bars' properties are strongly different when compressive and tensile performance are considered, particularly at elevated temperatures.
2. In the analysed case, the maximum compressive stresses in the BFRP bars were comparable to steel at room temperature. Maximum tensile stresses, though, were higher for BFRP than for steel at room temperature.
3. The compressive strength of the BFRP bars was higher than the value for concrete, but only for temperatures lower than 200°C. Therefore, low utilisation of such bars in reinforcing the concrete (with 35 MPa compressive strength at room temperature) may occur at elevated temperatures when compression is considered. This was also confirmed in the numerical analysis.

4. Different mode of failure was noted in both – numerical and experimental analyses – for the columns with steel and BFRP reinforcement, which may be attributed to the significantly lower stiffness of the BFRP bars.

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Analiza porównawcza prętów zbrojeniowych stalowych i BFRP w warunkach pożarowych

Słowa kluczowe: BFRP, zbrojenie niemetaliczne, pożar, temperatura, słup betonowy

Streszczenie:

Zbrojenie FRP zyskało znaczenie dzięki wysokiej wytrzymałości na rozciąganie, wysokiej trwałości i małego wpływu na środowisko. Wykazano ich przydatność jako zbrojenia wewnętrznego lub mocowanego z zastosowaniem systemów NSM (ang. Near Surface Mounted) w betonowych elementach zginanych, analizując również ich zachowanie w warunkach pożarowych. Niewiele jest natomiast opracowań dotyczących ściskania prętów i ściskanych elementów betonowych zawierających tego typu zbrojenie, zwłaszcza w warunkach podwyższonej temperatury. W artykule zaprezentowano

wyniki uzupełniających badań w zakresie oceny odporności ogniowej słupa ze zbrojeniem głównym BFRP (ang. Basalt Fibre Reinforced Polymer), na podstawie przedstawionych wcześniej analiz numerycznych. Przeprowadzono analizę porównawczą pod kątem temperatury, odkształceń i naprężeń słupa ze zbrojeniem głównym stalowym lub BFRP w badaniach odporności ogniowej. Symulacje numeryczne odporności ogniowej wybranych elementów mają odzwierciedlenie w przeprowadzonych wcześniej badaniach. Wyniki badań materiałowych (np. dynamiczna analiza mechaniczna DMA – ang. Dynamic Mechanical Analysis, analiza termograwimetryczna TGA – ang. Thermogravimetric Analysis, testy mechaniczne ściskania/rozciągania w temperaturze pokojowej i w wysokich temperaturach) na prętach BFRP zostały omówione we wcześniejszych pracach autorów.W pierwszej kolejności przeprowadzono analizę porównawczą dla relacji naprężenie-odkształcenie trzech materiałów (BFRP, stal i beton) dla różnych zakresów temperatur. Wyniki wcześniejszych własnych badań wykorzystano do ustalenia wytrzymałości na ściskanie w temperaturze pokojowej i podwyższonej oraz wytrzymałości na rozciąganie prętów BFRP w temperaturze pokojowej. Na podstawie danych literaturowych przyjęto współ czynniki redukcyjne do zmniejszenia wytrzymałości na rozciąganie i modułu sprężystości wraz ze wzrostem temperatury. W tym przypadku wybrano pręty FRP o podobnym składzie (ten sam typ matrycy – epoksydowa i zbliżona procentowa ilość włókien). Założenia dla betonu i stali przyjęto zgodnie z Eurokodem. Wytrzymałość betonu na ściskanie w temperaturze pokojowej przyjęto jako 35 MPa, ponieważ słup analizowany w symulacji numerycznej (ze zbrojeniem BFRP) byływykonany z podobnego betonu. Podobnie granicę plastyczności stali przyjęto jako 446 MPa, gdyż z takiej stali wykonano główne zbrojenie słupa ze stalowymi prętami głównymi w analizach numerycznych. Obliczenia przeprowadzono w dwóch etapach. Obciążenie mechaniczne zostało przekazane przez sztywny element w pierwszym kroku obliczeniowym (statycznym). Następnie w drugim kroku zamodelowano ogrzewanie słupa z wykorzystaniem oddziaływania powierzchniowego z amplitudą temperatury otoczenia w postaci, w której do każdego przyrostu czasu o 300 sekund przypisuje się odpowiednią wartość. Wartość współczynnika emisyjności przyjęto równą 0,85. Największą zaletą prętów FRP jest ich wysoka wytrzymałość na rozciąganie (dwukrotnie wyższa niż granica plastyczności dla stali). Jednak wytrzymałość na ściskanie jest porównywalna ze stalą nawet w temperaturze pokojowej. Wraz ze wzrostem temperatury do 100-200°C wytrzymałość BFRP na rozciąganie jest nadal znacznie wyższa niż granica plastyczności stali, ale wytrzymałość na ściskanie jest prawie znikoma w odniesieniu do stali. Porównując właściwości mechaniczne BFRP z betonem, pręty niemetaliczne mają znacznie wyższą wytrzymałość na ściskanie w temperaturze pokojowej, ale w temperaturze 200°C wpływ prętów może nie być zauważalny przy ściskaniu, lub nawet może spowodować osłabienie przekroju. W analizie numerycznej, pomimo porównywalnych rozkładów temperatury, naprężenia w głównych prętach różnią się znacząco pomiędzy słupem ze zbrojeniem BFRP i stalowym. Podczas gdy naprężenia w prętach BFRP są znikome (36 MPa, a mogą być nawet mniejsze lub pręty mogą zostać całkowicie wypalone lub zniszczone w warunkach rzeczywistych i odzwierciedlających je warunkach doświadczalnych), pręty stalowe w większości wytężonych obszarów nadal zachowują znaczny poziom naprężeń (204 MPa).

Na podstawie przedstawionych badań można sformułować następujące wnioski:

1. Właściwości prętów BFRP różnią się znacznie porównując ich wytrzymałość na ściskanie i rozciąganie, szczególnie w podwyższonych temperaturach.
2. W analizowanym przypadku maksymalne naprężenia możliwe do uzyskania w prętach BFRP podczas ściskania były porównywalne ze stalą w temperaturze pokojowej, natomiast wytrzymałość na rozciąganie była wyższa dla BFRP w temperaturze pokojowej.
3. Wytrzymałość prętów BFRP na ściskanie była wyższa niż dla betonu, ale tylko dla temperatury poniżej 200°C, dlatego wykorzystanie takich prętów do zbrojenia betonu (np. o wytrzymałości

na ściskanie 35 MPa w temperaturze pokojowej) może nie być efektywne w podwyższonych temperaturach, gdy rozważa się ściskanie. Potwierdziła to również analiza numeryczna.

4. Zaobserwowano inny sposób zniszczenia obu analizowanych słupów zarówno w analizie numerycznej, jak i doświadczalnej. Prawdopodobnie jest to wynik mniejszej sztywności zbrojenia BFRP w porównaniu do stali.

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