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INVESTIGATION ON APPLICATION OF BASALT MATERIALS AS REINFORCEMENT FOR FLEXURAL ELEMENTS OF CONCRETE BRIDGES

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Abstract. Basalt polymers are rather new materials for civil engineering; therefore, identification of peculiarities and limitations of application of such polymers in concrete structures (particularly bridges) is of vital importance. This paper experimentally investigates deformation behaviour and cracking of flexural elements, which are predominant parameters governing serviceability of the bridges. Unlike a common practice, the present study is not limited by the analysis of concrete beams reinforced with the polymer bars; it also considers effectiveness of basalt fibre reinforced polymer sheets for repairing the beams. The analysis has revealed that a combination of the high strength and elasticity polymer materials governs the effective repair of the beams by significantly increasing (up to 40%) the structural stiffness.

Keywords: reinforced concrete, basalt fibre reinforced polymer (BFRP), internal bars, external sheets, test data.

1. Introduction

Concrete is the most widely used material in civil engineering. Well designed, properly built and maintained reinforced concrete (RC) structures must serve for centuries, but, in reality, those structures suffer from aggressive environmental conditions: salt- or alkali-solution ingress, chloride attack, tidal waves, earthquake, etc. These factors cause cracking of concrete, corrosion of steel reinforcement, and, consequently, a complete deterioration of buildings. Thus, most of the infrastructure elements, such as bridges or offshore constructions, become deficient requiring permanent maintenance or repair. In Europe, almost half of the construction industry budget is spent on the repair and reconstruction of existing buildings (Cigna *et al.* 2003). According to a study conducted by the Federal Highway Administration (USA) in 2013, the 24.9% of the nation's 607 380 bridges were rated structurally deficient or functionally obsolete. According to the American Society of Civil Engineers Report Cards for America's Infrastructure in 2013, elimination of these deficiencies costs approx 11.3 billion EUR a year for 20 years. In China, only due to the corrosion, financial losses reach 2% of the Gross Domestic Product (Ke, Li 2008).

Depending on the degree of structural degradation, an engineer has to choose from several common repair methods (Gudonis *et al.* 2014; Miller 2006). In case of severe damages, the deteriorated structural element might be replaced by a new one. Alternatively, the load caring capacity might be restored by using an external strengthening. However, these methods might be rather expensive and time-consuming. Due to traffic-related growth of transportation costs, an extreme increase of the expenses follows the repair of the bridges. Therefore, it is not surprising that the huge financial investments and efforts of scientists and engineers from all over the world are made for improvement of structural and technical solutions of concrete structures and creation of new and efficient materials.

In order to prevent the corrosion of steel reinforcement, fibre reinforced polymers (FRP) were developed. The common types of FRP materials are carbon, glass, aramid, and basalt. Sim *et al.* (2005) splited FRP reinforcement into four general groups: 1) internal bars; 2) external bonding laminates/sheets; 3) near surface mounting rods, and 4) short fibres. The current study considers the first two types of the reinforcement.

Basalt fibre reinforced polymer (BFRP) is of a low price and has a high strength, resistance to chemical attack, and relatively simple handling at site. However, there are no design guides, recommendations, or standards for

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BFRP. This is related to a very limited number of relevant researches e.g., High (2014) and Zhishena *et al.* (2012). The current study is dedicated to experimental investigation of RC beams with internal and external BFRP reinforcement.

The present manuscript investigates deformation behaviour and cracking of flexural elements, i.e., the predominant parameters governing serviceability of the concrete bridges, reinforced with BFRP materials (Timinskas *et al.* 2013). The paper reports new experimental results of 4 BFRP RC beams subjected to a 4-point loading. Unlike a common practice, the study is not limited by the analysis of the RC beams with internal BFRP bars; it also investigates effectiveness of application of external BFRP sheets for repairing the beams. Herein, the term effectiveness is related to a capability of the sheets to restore the structural stiffness. The tests were carried out in 2 load cycles. At the 1st stage, the beams were tested until failure, after that, strengthened with BFRP sheets.

2. Experimental program

2.1. Material properties and characteristics of the specimens

Being a part of a larger test program (Kaklauskas *et al.* 2008) supported by the Research Council of Lithuania, the present study employs original notations of the specimens. Letter "*S*" refers to the type of elements (in Lithuanian "*Sija*" = "*Beam*"), "*Bnm*" refers to non-metallic (basalt) reinforcement. The test beams with a rectangular cross-section of 300×280 mm had a nominal length of 3000 mm. Sand coated BFRP bars Rockbar (basalt reinforcement bars from the Limited Liability Company Galen (Russia)) with nominal diameters of 12 mm and 16 mm were used for reinforcing the tensile zone, whereas the compressive reinforcement was made of steel bars (Ø6 mm). The steel stirrups (Ø10 mm) were spaced each 100 mm in the shear zone (Fig. 1). Three beams (*S1-4-12Bnm*, *S2-4-12Bnm*, and *S3-4-16Bnm* (Fig. 1a)) were designed to unify d/h ratio in accordance to the general reinforcement layout specified in the test program (Kaklauskas *et al.* 2008). Thus, the BFRP bars were placed outside the stirrups to maintain the minimum cover requirements. The main parameters of the materials and the geometry of specimens are presented in Table 1 and Table 2. A notation of the cross-section is evident from Fig. 1a. Remaining parameters in the tables are BFRP reinforcement ratio (ρ_f); age of the specimens at the testing day (t); and compressive strength of the concrete cylinder Ø150×300 mm (f_{cm}).

The beams were cast using an instrumental formwork (Fig. 1b). The concrete grade of C35/45 was used. The concrete mixture is given in Table 3. After casting, the beams were unmoulded in 2–3 days, after that, the specimens were cured at the average relative humidity (*RH*) of 40% and temperature of 19 °C.

2.2. Test setup and experimental results

The beams were tested under a 4-point bending scheme with the 850 mm shear spans as shown in Fig. 2a. The specimens were loaded using a 100 kN hydraulic jack in a stiff testing frame. The testing equipment summed up

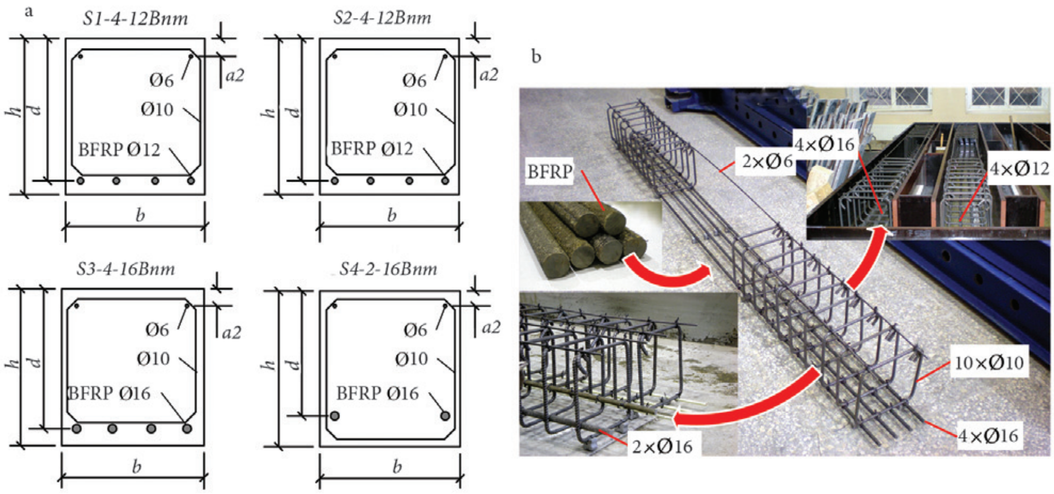

Fig. 1. Reinforcement schemes of the beams: a – cross-sections of the beams; b – preparation for casting

Table 1. Main characteristics of the experimental beams

No.	Beams	h, mm	b, mm	d, mm	ρ_f, %	t, days	f_{cm}, MPa	BFRP sheets	Glue
1	*S1-4-12Bnm*	303	280	273	0.59	176	45.0	3	EPOX
2	*S2-4-12Bnm*	302	278	272	0.60	166	45.0	2	EPOX
3	*S3-4-16Bnm*	304	281	271	1.06	175	45.0	2	POLI
4	*S4-2-16Bnm*	302	282	229	0.62	169	45.0	3	POLI

with the self-weight of the beam was acting as 3.5 kNm moment at the mid-span. The test was performed with small load increments (2 kN) and paused for short periods (about a minute) to take readings of the mechanical gauges (Fig. 2) and to measure crack development. On average, it took from 60 to 80 loading steps with total test duration of 3 hours.

Using mechanical gauges, the strains of concrete surface were measured throughout the length of the pure bending zone on a 200 mm gauge length. As shown in Fig. 2, 4 continuous gauge lines were located at different heights. The 2 outer gauge lines were placed along the top and bottom reinforcement, whereas 2 inner lines were located 60 mm off these lines. The vertical displacements in pure bending zone and near the supports were measured by linear variable displacement transducers (LVDT L 1–8 (Fig. 2a)). Slip of the BFRP bars at both ends of the beams have been also recorded using Linear variable differential transformer (LVDT) (Fig. 3). A load cell was used to measure the applied load. Almemo 2890-9 data logger was used to collect recordings from the LVDT and the load cell.

A test program consisted of two stages. In the 1st stage, 4 concrete beams reinforced with BFRP bars were tested until failure. The failure was determined by an increased rate of deflections (or concrete surface deformations) and it was related to the initial crushing of compressive concrete or the initial collapsing of shear zone. The relatively small load increments, used in the tests, allowed determining the critical loading stage rather precisely. The obtained ultimate load capacity is given in Table 4. In the 2nd stage, these beams were strengthened with BFRP sheets (Fig. 4a) and tested again. BFRP sheets with the weight-per-area ratio of 400 g/m^2 were selected for the strengthening. The beams were strengthened with different number of BFRP layers using 2 different epoxy adhesives (Table 1): low elasticity – Epox (Epoxy Base Resin from the Limited Liability Company "Kompozit" (Ukraine)) and elastic – Poli (Polyforce Plus EP – Epoxy Base Resin from the Polyforce International Inc. (Canada)). Two beams *S2-4-12Bnm* and *S4-2-16Bnm* were severely damaged at the 1st testing stage. One of them (*S2-4-12Bnm*) was additionally wrapped in the shear zone (Fig. 4).

Table 2. Mechanical properties of the BFRP materials

No.	Type	Ultimate strength, $f_{f,u}$, MPa		Modulus of elasticity, E_f, GPa	
		Experiment	Nominal	Experiment	Nominal
1	Bar Ø12	–	1000	–	45
2	Bar Ø16	–	1000	–	45
3	Sheets	169.6	–	15.5	–

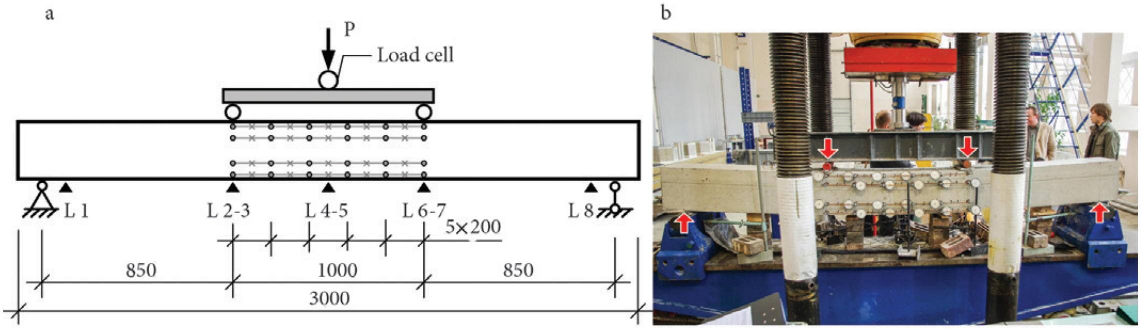

Fig. 2. Test set-up: a – layout of mechanical strain gauges and LVDT; b – test set-up

Table 3. Concrete mix proportions

Material	Amount, kg
Sand 0/4 mm	910 ± 2%
Crushed aggregates 5/16 mm	940 ± 2%
Cement CEM I 42.5 N	415 ± 1%
Water	174 ± 5%
Concrete plasticizer Stachement 2067	3.32 ± 2%

Fig. 3. Slip measurement of BFRP bar at the end of the tested beam

The final crack pattern of the specimens *S1-4-12Bnm* and *S3-4-16Bnm* before and after strengthening (corresponding to the 1st and 2nd test stages) are shown in Fig. 5. Grey colour indicates the cracks from the 1st testing stage as the black colour shows the ones from the 2nd stage.

Using the methodology described in the references (Gribniak *et al.* 2008, 2013b) and the test results (recordings of the deflections and the concrete surface strains), the moment-curvature diagrams have been derived. Fig. 6 presents these diagrams for the beams before and after strengthening.

2.3. Discussion of the results

Recent investigation on reinforced concrete elements strengthened with BFRP sheets, conducted by the authors (Gribniak *et al.* 2014), revealed that the mechanical properties (elasticity and strength) of adhesives govern the failure mode. Thus, it is considered as an important input for the design of strengthened structural elements. Insufficient elasticity of the applied adhesives as well as inappropriate selection of the stiffness of external reinforcement (i.e., the number of BFRP sheets is highly out of proportion to the stiffness of the strengthened element) lead to failure of the strengthening at the early loading stage. Frequently, this is related to the bond loss of the FRP sheets.

In the current study, the bond failure of BFRP materials did not occur. Mainly, it is related to the high elasticity of the BFRP materials (Table 2). This allows investigating deformation behaviour of the beams without consideration of slip effects.

Table 4. Characteristics of the tested beams

No.	Beam	Experimental bending moment			Stiffness increase at the service load M_{serv}, %	Restored load-bearing capacity, %
		Cracking load, kNm	Ultimate load			
			I loading, kNm	II loading, kNm		
1	*S1-4-12Bnm*	20.27	104.15	92.69	43.4	89.0
2	*S2-4-12Bnm*	–	74.39	74.17	13.0	99.7
3	*S3-4-16Bnm*	21.28	124.54	120.56	28.5	96.8
4	*S4-2-16Bnm*	–	71.40	46.70	31.5	65.4

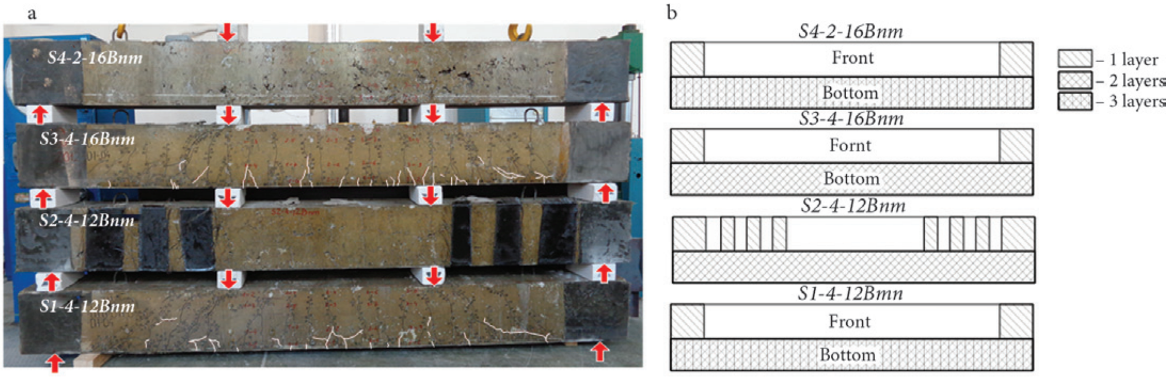

Fig. 4. Strengthening with BFRP sheets: a – tested beams; b – strengthening schemes

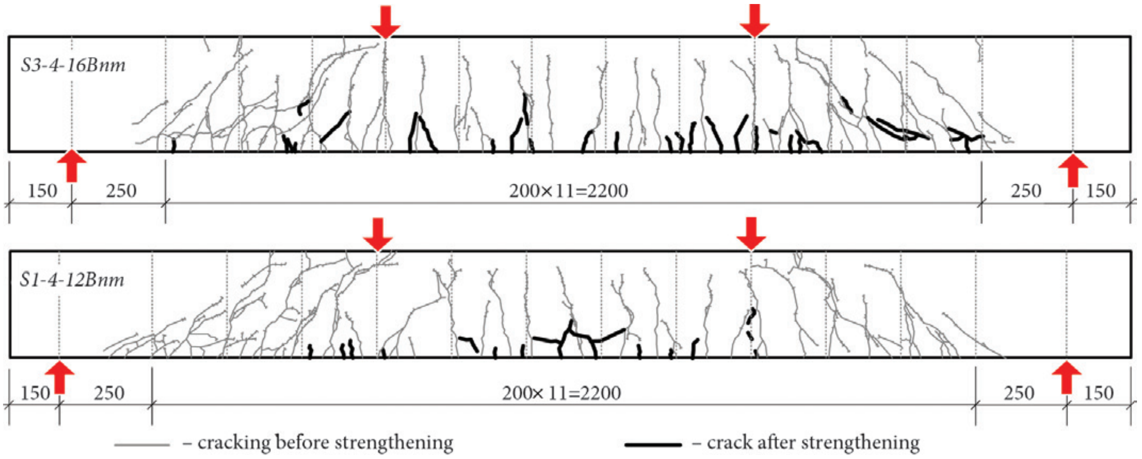

Fig. 5. Crack pattern of the tested specimens (measuments in mm)

The obtained experimental results are discussed considering 2 main aspects of the structural behaviour: load-bearing capacity and structural stiffness. The load-carrying capacity of the damaged beams was restored well above the service load (Fig. 6). However, it was below (in two cases to a significant extent) the ultimate capacity obtained at the 1st testing stage. The load-bearing capacity of only one (*S2-4-12Bnm*) of the 4 tested beams was fully restored, reaching 99.7% of the original value (Table 4). Unlike the others, this beam was additionally strengthened in the shear zone (Fig. 4) that might have contributed to the increase in load-carrying capacity.

A degree of the restored load capacity of all the strengthened beams is presented in Table 4. It was found that the beam *S4-2-16Bnm* possesses of only 65.4% of the restoration degree. This is mainly due to the exceptionally high damage level of concrete reached in the 1st loading stage. In order to quantify the restoration of the load capacity, it is necessary to perform a comprehensive experimental program considering an adequate number of BFRP sheets and mechanical properties of adhesives as well as BFRP sheets.

Another considered issue is related to the structural stiffness of the beams. It is known that a number of cracks is closely related to the overall stiffness of RC member (Gribniak *et al.* 2013a; Jakubovskis *et al.* 2014). The application of BFRP sheets significantly increased number of cracks (twofold increase in the pure bending zone, Fig. 5). Such increment leads to the reduction of the crack opening width. Although irrelevant for the durability, this is rather important from the aesthetic point-of-the-view.

It is evident from Table 4 that the flexural stiffness increased by 43.4%, 13.0%, 28.5% and 31.5% for the strengthened beams *S1-4-12Bnm*, *S2-4-12Bnm*, *S3-4-16Bnm* and *S4-2-16Bnm*, respectively. The higher stiffness increase is observed in the beams with higher number of BFRP layers (*S1-4-12Bnm* and *S4-2-16Bnm*). The change in stiffness before and after strengthening is determined at the load level M_{serv}, which is set equal to 55% of the theoretical load-bearing capacity of the beam determined limiting stresses in the reinforcement to 500 MPa (as recommended in the technical documentation by Schöck Bauteile GmbH (Germany)).

Moreover, due to low modulus of elasticity and high corrosion resistance of BFRP materials, the limitation of deformations in most cases is a governing criterion in the design of bridge elements. Structures with high strength reinforcement such as BFRP has an advantage in regard to mild steel of not having large residual stresses and strains after removing the load. This facilitates effective involvement of both internal and external reinforcement into a composite action. Thus, the application of the combined BFRP reinforcement is rather effective as a mean for restoration of the structural stiffness.

3. Conclusions

The paper experimentally investigates deformation and cracking behaviour of concrete beams reinforced with basalt fibre reinforced polymer bars and strengthened with basalt fibre reinforced polymer sheets. The test program consisted of two stages: 4 concrete beams reinforced with basalt fibre reinforced polymer bars were preloaded until

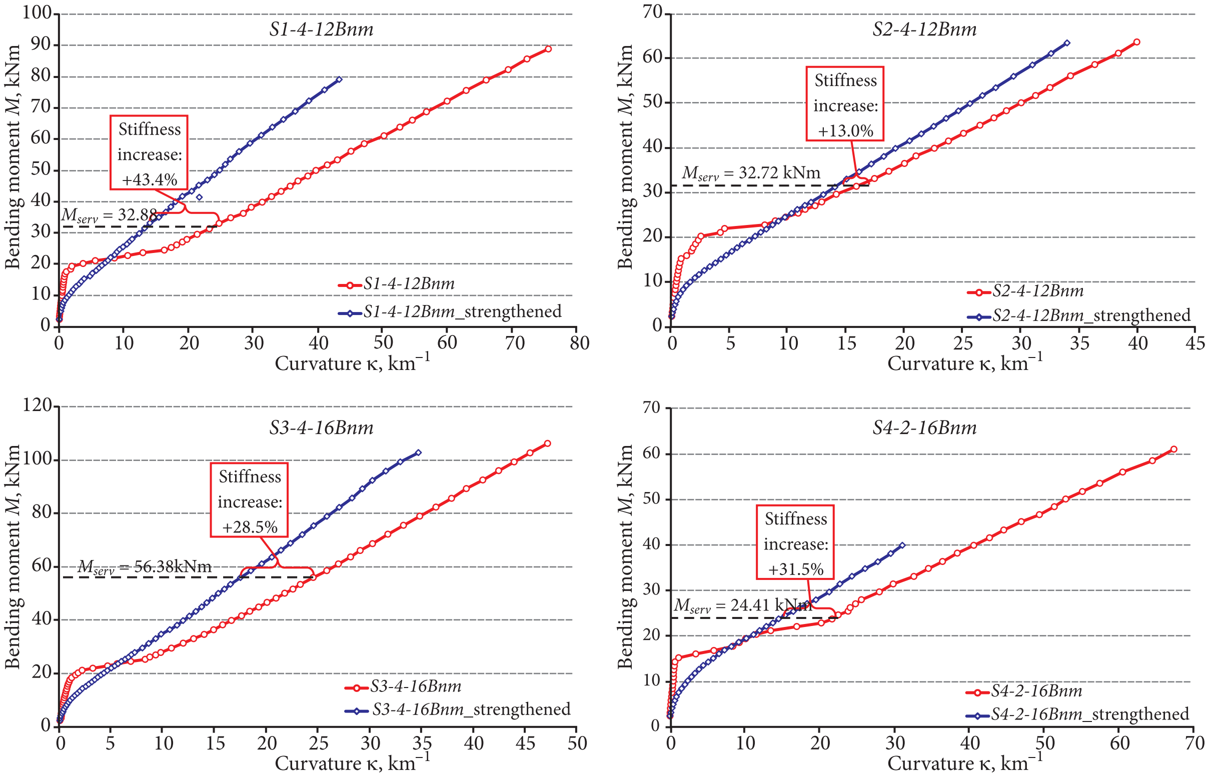

Fig. 6. Moment-curvature diagrams of the beams with BFRP reinforcement before and after strengthening

failure; then strengthened with the polymer sheets and tested again. The structural stiffness as well as the load-bearing capacity before and after strengthening were assessed. Throughout the experimental studies presented herein, the results provide a fundamental information for the application of basalt fibre reinforced polymer products in concrete bridge elements subjected to bending. From the performed analysis, the following conclusions are drawn:

1. Due to high elasticity and high strength of basalt fibre reinforced polymer materials, the bond failure of the polymer reinforcement did not occur. This allows assessing deformation behaviour of the beams without considering the bond-slip effects.

2. The considered combination of internal and external basalt fibre reinforced polymer reinforcement enables to restore the stiffness of strengthened reinforced concrete elements efficiently. The minimum increase of stiffness for the beams was 13%, whereas the average increment was nearly 30%. The combined application of basalt fibre reinforced polymer materials has a potential to increase the structural stiffness and to be used as an alternative to steel reinforcement in new or existing concrete bridge elements.

3. In order to validate the results of this limited study, a further comprehensive experimental investigations aiming at deformation and, particularly, load-carrying capacity are needed. Special emphasis in these tests has to be made on the long-term behaviour.

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