Analysis of tests results indicates that styrene-acrylic co-polymer additive even at the level of 5% of cement mass results in significant reduction of concrete shrinkage strains. It is due to penetration of cement matrix with the polymer membranes that surround cement and aggregate grains forming the spatial structure of honey-comb type. Additional favorable influence of polymer is the fact that polymer membranes surround the cement grains restricting the water access and thus slowing down the cement hydration process. Products of hydration, especially portlandit crystals, are characterized with favorably changed fine-crystal structure. Polymer membranes penetrating cement matrix indicate ability to bridge shrinkage micro-cracks (Schorn, 2002).

4 CONCLUSIONS

Conducted research program made it possible to formulate the following general conclusions:

- Addition of styrene-acrylic co-polymer at the amount of 5÷11% of cement mass allows for increasing the concrete resistance to scaling due to the composite structure sealing by polymer membranes that penetrate the cement matrix and to favorable modification of dimensional characteristics of concrete porosity.
- Obtaining concretes with high and very high quality for scaling resistance is possible by reducing w/c ratio below the value of 0,40 and by dosing styrene-acrylic co-polymer additive within the range of 8÷11% of cement mass.
- Application of styrene-acrylic co-polymer allows for significant (35÷48%) increase in concrete bending strength as well as for reducing the shrinkage strains to the level of 0,1 mm/m - cement-polymer materials of this type may be thus classified as low-shrinkage which is particularly important in its applications for concrete structures repairs.

Trial mixes and obtained tests results made it possible to produce the appropriate cement-polymer concrete mix for breakwater structure repair in Gdynia Harbor. As optimal, due to its good scaling resistance at the presence of sea water as well as low values of shrinkage strains with obtained assumed level of strength, the formula with w/c ratio equal to 0,38 and styrene-acrylic co-polymer additive dosage level of 8% of cement mass was finally selected.

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Effect of specimen size on the strength of FRP-confined concrete

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ABSTRACT: Some FRP confinement models available in the literature are based on standard cylindrical specimens and others are based on mixed sizes of cylindrical specimens. The accuracy of the latter models are questionable because it depends on the percentage of increase in strength between unconfined and FRP-confined specimens and on the ratio of strength increase among the different sizes of specimens. The question which can be raised here is: is there a need to introduce a size factor for the test results which are based on non-standard sizes of cylindrical specimens before using them in developing analytical models for FRP-confined concrete? The output of this study answers this important question. Thirty seven concrete cylinders with three different sizes have been tested. Thirteen specimens were unwrapped to be used as baseline for comparison, whereas twenty four cylinders were wrapped with layers of CFRP jacket. Studied parameters were specimen size and confinement stress ratio.

1 INTRODUCTION

Fiber-reinforced polymer (FRP) confinement of reinforced concrete columns has been shown to be a very effective technique for structural enhancement. Indeed, numerous studies (Al-Salloum 2008; Demers and Neale 1999; Haroun and Elsanadedy 2005) have demonstrated that wrapping FRP sheets around a circular column can increase its strength considerably as well as provide improved ductility. However, most experimental studies to date on the confinement of concrete columns with FRP have been conducted without considering the possible scale factors involved. The behavior of small specimens may be affected by the restraining influence of the end-bearing plates, which can lead to local non-homogeneities that will cause higher standard deviations and produce results that are not representative of larger specimens (ASTM 1995). Most codes provide weighting factors for concrete strengths measured from cylinders having a diameter different than the standard value of 150 mm. Nevertheless, in spite of all these inconveniences, small specimens are widely used since they are more economical, requiring less material, smaller molds, less expensive testing equipment, and limited space for storage. They are also easier to handle, therefore saving time and reducing the risk of damage during handling.

As there is currently a great interest in developing design guidelines for FRP-strengthened concrete columns, it is important to ensure that the proposed equations are truly representative of the actual behavior of full-scale columns. Since most of the available data regarding FRP-confined concrete have been generated from tests on small-scale cylinders, the validation of these results and their applicability to large-scale columns is of great practical interest.

Sener el al. (2004) studied the size effect on axially loaded reinforced concrete. The tests specimens were geometrically similar pin-ended concrete columns of different sizes (in the ratio 1:2:4) giving slenderness ratios of 9.7, 18.0, and 34.7. The columns had square cross sections of sides 50, 100, and 200 mm, and varied in length from 0.14 m to 2.08 m. It was observed that for all slenderness ratios, the failure loads exhibited a size effect in which the nominal stress at maximum load (failure load divided by cross-sectional area) decreased as the size was increased. This contradicts the current design codes, which make no allowance for such size effect, and indicates that the failure is governed by fracture mechanics. Research on size effect on FRP-confined concrete is very limited in the literature. Theriault et al. (2004) investigated experimentally the influence of slenderness ratio and specimen size on axially loaded FRP-confined concrete columns, and the results have been compared to theoretical models and experimental results gathered from the published literature. Three different specimen diameters and two slenderness (length-to-diameter) ratios, combined with two FRP-confinement materials, were varied as parameters. According to the statistical analysis of the results, it was shown that conventional FRP-confined concrete cylinders can effectively be used to model the axial behavior of short columns.

This study focuses on various aspects of the effects of the size of FRP-confined concrete cylinders. Using the same concrete mix, size effects are investigated through tests on specimens having three different diameters with the same slenderness ratio (*H/D*). A total of 37 concrete specimens were tested under uniform uniaxial compression. The data recorded included compressive loads in addition to axial and radial strains.

2 EXPERIMENTAL PROGRAM

2.1 *Test matrix*

Details of test matrix are listed in Table 1. As indicated, three different sizes of cylinders have been used. Test specimens have been designated using 4 character naming code. The first letter U & W indicates unwrapped or wrapped specimens, respectively. Except for cylinders with 50-mm diameter, the second number in the designation denotes number of CFRP layers. The next number indicates the diameter (in mm) of test specimens; whereas, the last is for the specimen number. For example, "W2-100-3" is wrapped with two layers of CFRP, with 100-mm diameters and is the third specimen.

Table 1: Test matrix used in this study

Specimen designation	Diameter (mm)	Height (mm)	No. of CFRP layers	No. of repetitions
UW50	50	100	-	4
UW100	100	200	-	4
UW150	150	300	-	5
W50	50	100	1	4
W1-100	100	200	1	5
W2-100	100	200	2	4
W1-150	150	300	1	5
W2-150	150	300	2	2
W3-150	150	300	3	4
Total No. of specimens				37

2.2 *Preparation of specimens*

The nominal 28-day specified design strength of the concrete used ranged from 38 MPa to 44 MPa. The quantities of ingredients used in the concrete mix are shown in Table 2. A total of 37 unreinforced cylinders with different cross-sectional sizes (50 x 100 mm, 100 x 200 mm, 150 x 300 mm) were constructed. After 28 days of curing, wrapped specimens were carefully sandblasted and voids and deformities on the surface of the specimens were filled using gypsum paste. The two part epoxy system used was thoroughly hand-mixed for at least 5 minutes before use. The CFRP laminates were then applied directly onto the surface of the specimens providing unidirectional lateral confinement in the hoop direction. Special attention was taken by the installers to eliminate any voids between the FRP laminates and the concrete substrate. All wrapped specimens were stored at room temperature for at least 7 days before testing in order to ensure that enough time had passed for the epoxy to cure. Prior to loading the specimens on to the test machine, the ends of the jacket were ground smooth to remove any uneven edges. Representative samples of unwrapped and wrapped cylinders are shown in Fig. 1. Mechanical properties of CFRP laminates are listed in Table 3.

Table 2: Proportions of ingredients used for concrete mix

Ingredients	Quantity (for 1 m^3)
Cement (type 1)	350 kg
Silica sand	585 kg
Washed sand	195 kg
10 mm aggregate (3/8)	315 kg
20 mm aggregate(3/4)	735 kg
Free water	175 kg
Admixture	0.6% by weight of cement

Table 3: Mechanical properties of CFRP material used in this study

Thickness per layer (mm)	Tensile modulus (GPa)	Tensile strength (MPa)
1.0	77.30	846

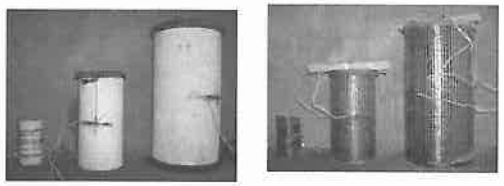


Figure 1: Test specimens.

2.3 *Instrumentation and test procedure*

All cylinders were capped with sulfur to ensure parallel surface and to distribute the load uniformly in order to reduce eccentricity. All specimens were instrumented by two horizontal strain gages mounted at its mid-height to record the lateral strains during the experiment. In order to measure axial strains, each specimen was fitted with two LVDTs that were mounted on two round sleeves around the specimen. The sleeves were attached to the specimen with pin-type support that would not affect the dilation of concrete. The testing was performed using 2000-kN hydraulic testing machine equipped with a moving piston that exerts an axial force. Test was controlled by displacement till failure of cylinders. Layout of instrumentation is presented in Fig. 2.

(a) 50-mm cylinders (b) 100-mm cylinders (c) 150-mm cylinders

Figure 2: Instrumented cylinder specimens ready for testing

3 TEST RESULTS AND DISCUSSION

Failed specimens can be observed from Fig. 3 for representative samples of unwrapped and wrapped cylinders. For unwrapped specimens, mode of failure can be characterized by shearing and splitting of concrete. The performance of wrapped specimens was consistent. Prior to the failure, cracking noises were heard, indicating the start of stress transfer from the dilated concrete to the CFRP jacket. The failure was gradual, ended with a sudden and explosive noise. It was characterized by crushing of concrete followed by cutting of the CFRP laminates at the middle portion of the specimen. The jacket rupture started at its mid-height and progressed up and down. The sudden and explosive nature of the failure indicates the release of tremendous amount of energy as a result of the uniform confining stress provided by the jacket. Inspection of the failed specimens showed good contact between the jacket and the concrete indicating that no debonding took place at any stage throughout the loading process. Summary of test results is listed in Table 4 as average values for peak axial stress, peak axial strain and peak lateral strain. In addition, stress-strain curves were generated for all specimens as shown in Figs. 4 to 6.

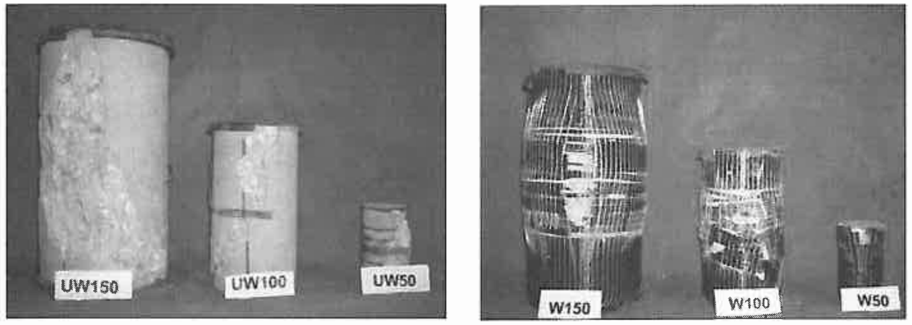


Figure 3: Mode of failure of test specimens

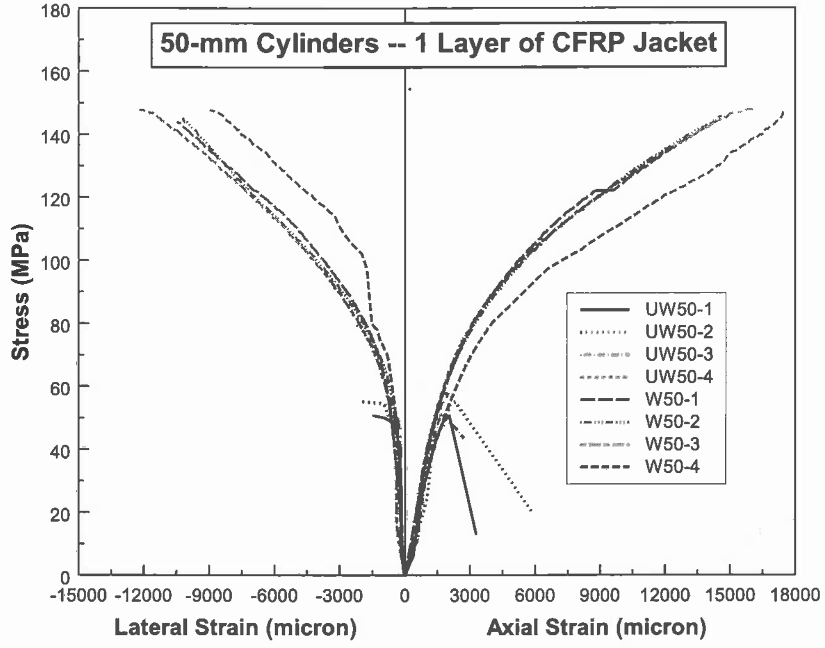
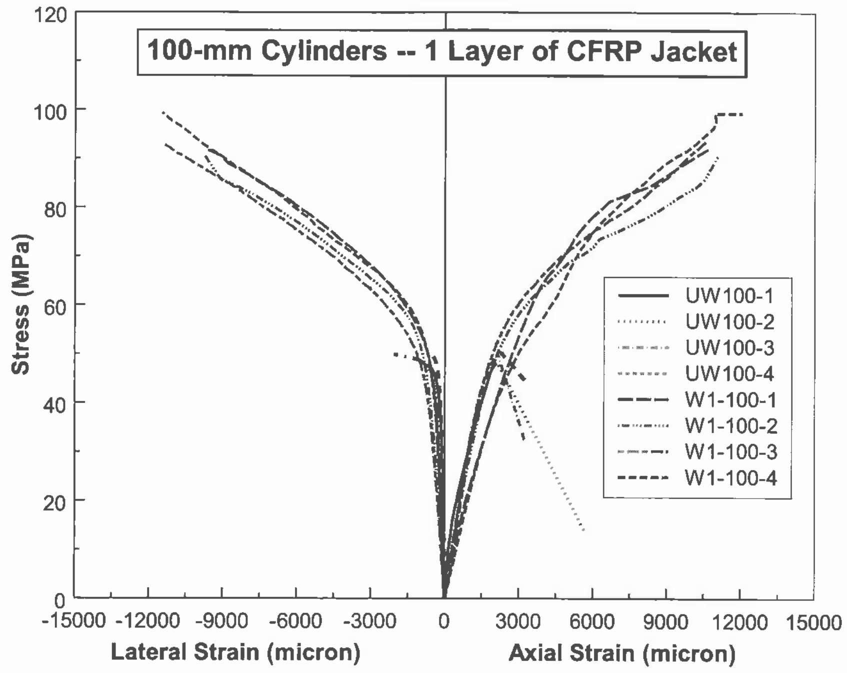
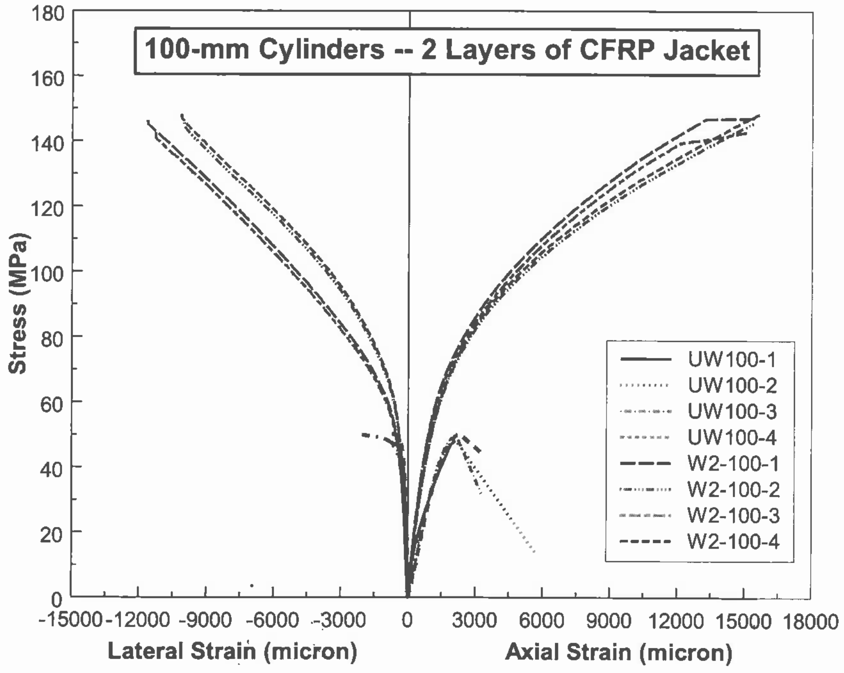


Figure 4: Stress-strain curves for 50-mm cylinders

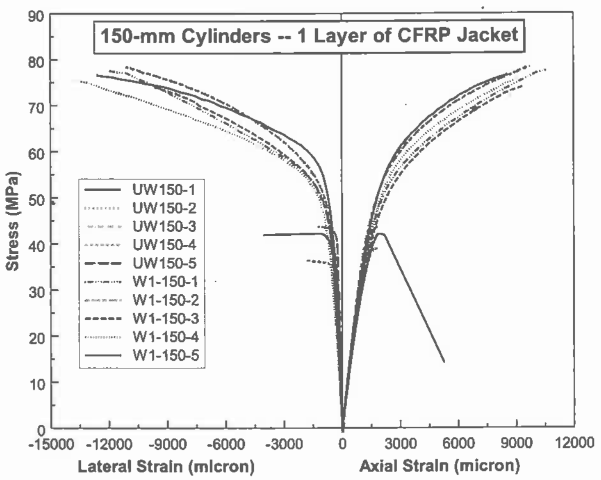


(a) Specimens with 1 layer of CFRP jacket

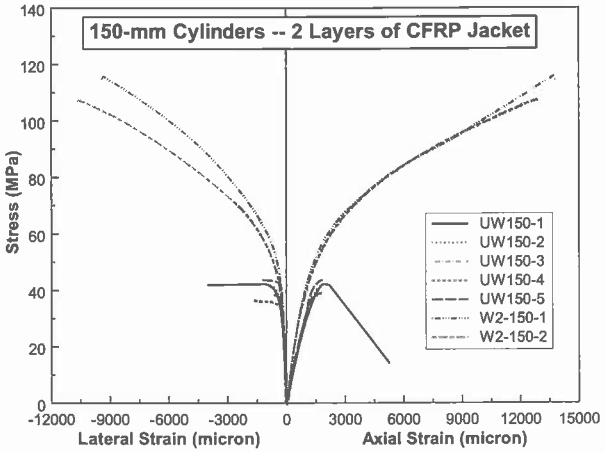


(b) Specimens with 2 layers of CFRP jacket

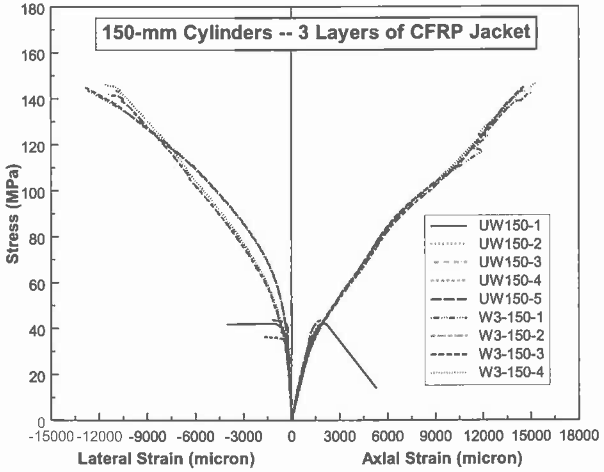
Figure 5: Stress-strain curves for 100-mm cylinders



(a) Specimens with 1 layer of CFRP jacket



(b) Specimens with 2 layers of CFRP jacket



(c) Specimens with 3 layers of CFRP jacket

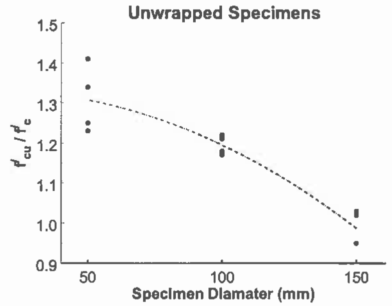
Figure 6: Stress-strain curves for 150-mm cylinders

Table 4: Summary of test results

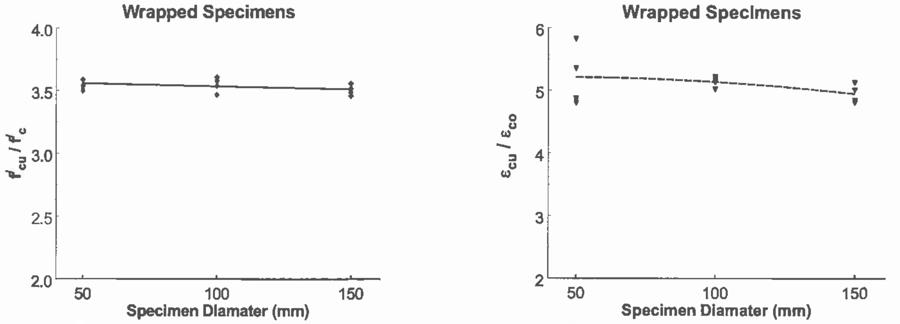
Specimen designation	Peak axial stress* (MPa)	Peak axial strain* (micron)	Peak lateral strain* (micron)
UW50	53.8	3440	1316
UW100	49.1	3605	1138
UW150	41.1	3616	1172
W50	146.2	15625	10479
W1-100	94.5	10907	10323
W2-100	146.0	15410	10779
W1-150	76.4	9445	11807
W2-150	111.5	13353	10071
W3-150	144.2	14852	12151

*average values of tested specimens

In order to study the effect of specimen size on ultimate strength of unconfined concrete, the relationship between specimen diameter and strength ratio (ratio of compressive strength, f'_{cu}, to compressive strength of standard 150-mm cylinder, f'_c) was generated as displayed in Fig. 7(a). The size effect is pronounced for unconfined concrete. However, the same was not true for CFRP-confined specimens. Fig. 7(b) presents the relation between specimen diameter and strength enhancement ratio (ratio of confined concrete strength, f'_{cu}, and unconfined compressive strength of standard 150-mm cylinder, f'_c). In addition, Fig. 7(c) displays the relation between cylinder diameter and strain enhancement ratio (ratio between ultimate compressive strain of confined concrete, ε_{cu}, and ultimate strain of unconfined concrete, ε_{cu}, taken as 0.003). It is clear that size effect is insignificant on both strength and strain enhancement of FRP-confined concrete. Accordingly, there is no need to introduce a size factor for the test results which are based on non-standard sizes of cylindrical specimens before using them in developing analytical models for FRP-confined concrete.



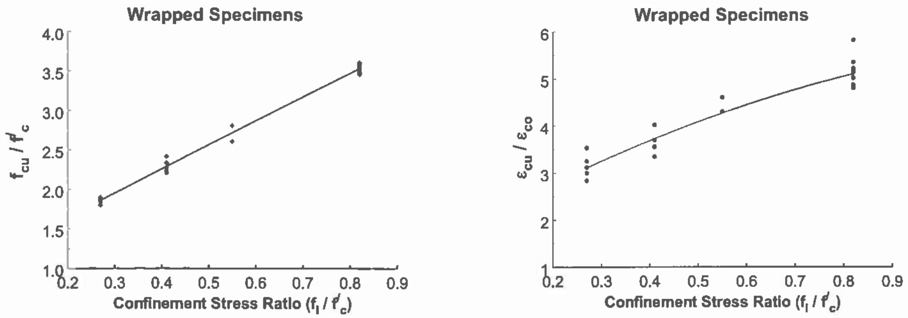
(a) Unwrapped – ultimate strength ratio



(b) Wrapped – strength enhancement (c) Wrapped – strain enhancement

Figure 7: Effect of specimen size on strength and strain enhancement

Due to the insignificant effect of specimen size on strength of FRP-confined concrete, all recorded data for CFRP-confined specimens used in this study can be mixed altogether to study the effect of confinement stress ratio (ratio of confinement stress provided by CFRP jacket, f_l, and unconfined compressive strength of standard 150-mm cylinder, f'_c) on both strength and strain enhancement as shown in Figs. 8(a) and 8(b). It is evident that as the confinement stress ratio increases the gain in strength and ductility increases for FRP-confined concrete.



(a) Strength enhancement

(b) Strain enhancement

Figure 8: Effect of confinement stress ratio on strength and strain enhancement

4 CONCLUSIONS

An experimental investigation was reported on the effect of specimen diameter on increase in strength and ductility under axial compression achieved by FRP-wrapping concrete cylinders. From conducted experimental testing, it is concluded that no significant variations occur in measured compressive strength when different sizes of FRP-confined concrete cylinders were used. But there is an effect for unwrapped cylinders. As a result, there is no need to introduce a size factor for the test results which are based on non-standard sizes of cylindrical specimens before using them in developing analytical models for FRP-confined concrete. For all FRP-wrapped specimens, it is evident that as the confinement stress ratio increases the gain in strength and ductility increases.

ACKNOWLEDGEMENT

The financial support from the research center at college of engineering of King Saud University is gratefully acknowledged.

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Sensor based CFRP – monitoring and strengthening of concrete members

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ABSTRACT: The load bearing behaviour of Carbon Fibre Reinforced Polymer (CFRP) is significantly influenced by the properties of the matrix, the fiber and the interface between both. During the last ten years an increasing amount of CFRP applications to rehabilitate damaged concrete elements was observed. Thereby some important disadvantages of the brittle materials must be considered, for example the low ductility of the bond between CFRP and concrete and brittle failure of FRP. With embedded sensor systems it is possible to measure crack propagation and strains. In this paper a sensor based CFRP system will be presented, that can be used for strengthening and measuring. On the basis of four point bending tests on beams (dimensions of 700 x 150 x 150 mm) the potential of the system is introduced. Primarily a comparison of two different measurement methods (Strain Gauge and Fiber Bragg) is shown.

1 INTRODUCTION – CARBON FIBER REINFORCED POLYMER

1.1 Development status

The strengthening and retrofitting of reinforced concrete structures become an increasing importance in the modern reinforced concrete construction. Reasons are the rising age of existing buildings as well as the necessity for change of use. For the rehabilitation of concrete structures there are different effective possibilities like the additional reinforcement of cross section, the change of the static system, injections and the prestress of the reinforcement. Particularly the additional reinforcement of the cross section is interesting, because it is possible to avoid complex changes at the static system. Besides shotcrete or concrete topping the use of glued reinforcement has become very popular. In many cases the reinforcement are plates which consist of steel or Fiber Reinforced Polymer (FRP). The bond between reinforcing plate and the structural element can be realized with a cold-curing resin. If steel plates are used, the reinforcement will be consistent to the normal reinforced concrete concerning bearing capacity and deformation behavior. One disadvantage of steel plates can be seen in the warranty of the durability. This is caused by the high risk of corrosion in the area of contact between steel and adhesive. Accuracy and the execution of metallic bright steel surfaces must be realized for good achievements. By the use of fiber reinforced polymer plates it is possible to minimize the risk of corrosion. Thereby these plates have a high tensile strength and low weight. The mainly used raw materials for the reinforcing fibers are glass and carbon. These fibers are embedded and fixed in an epoxy resin. But the use of glass fibers causes some problems. Compared with steel Glass Fiber Reinforced Polymers (GFRP) has only a small elastic modulus. It results in huge cross sections of the plates to assure the same extensional stiffness like in steel plates. The high tensile strength of glass fibers can not be accomplished. An economical use in the field of reinforcement is not possible in many cases. However, it is possible to avoid this problem if carbon fibers are the reinforcing material.