Polymeric composite laminate to increase the performance of natural stones

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Abstract - Low mechanical resistance and high weight restrict use of natural stones in applications where tensile or flexural capacity is required together with a low weight, such as for long spans or thin sections (e.g., cladding, countertops, desktops). The use of composite laminates as external reinforcement both to increase the mechanical resistance and to decrease weight of natural stone is investigated. High strength glass/epoxy laminates were bonded to the lower surfaces of marble and granite beams, and 3-point bend and short-beam tests were performed on reinforced and unreinforced specimens. Results indicate that external composite reinforcement can increase the mechanical property of both types of stone up to an order of magnitude as compared to unreinforced control samples.

Keywords- marble, granite, glass/epoxy laminate, 3-point bendtest, short-beam test

I. Introduction

Natural stone is generally used in construction and in building furniture since a long time. Recently, it has been used to decorate the environments for its aesthetic properties. However, material properties limit its applications. Because of its brittle nature and inherent defects, the strength of stone in tension is considerably less than its strength in compression. Typically the tensile strength of a rock type is exceeded by its compressive strength by one to three orders of magnitude. The disparity between compressive and tensile strength can limit the use of stone in applications where tensile and flexural strength capacity is required, such as for long spans or thin sections.

Mechanical and chemical weathering processes adversely affect the durability and, ultimately the strength of stone. The atmosphere, water, dissolved salts, acid rain and temperature fluctuations act as agents of decay, inflicting visible damage to stone as a decay, as demonstrated (Winkler, 1994). Cohen and Monteiro (1991) have shown that limestone and granite, are affected by weathering agents and are particularly susceptible to superficial dissolution caused by carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitric acid (NOx) dissolved in water as acid rain. It is evident that the weathering results in a loss of strength in natural stone.

Reinforcement provides stone members with flexural strength required for use in long spans, columns and slabs. However, in some cases, reinforced stone may fail to perform to its desired capacity because of faulty design, use of inferior materials, poor construction practices and insufficient maintenance. If such a problem occurs early in a structure's service life, repair and strengthening of the concrete sections may be more favorable than replacement or reconstruction of the failing members.

During the 1960s, researchers in South Africa and France investigated the use of external steel reinforcing to strengthen existing concrete bridges and buildings. Thin steel plates were bonded with epoxy to the tension face of concrete beams to provide additional local stiffness. Subsequently, Mays (1985) has applied this technique to reinforce concrete members in Europe, the United Kingdom, Japan, New Zeland, South Africa and the United States. Since steel plates are readily available and relatively inexpensive, repair of structures by externally bonded reinforcement is an attractive alternative to replacement. However, corrosion of the external metal plate remains a problem.

Fibre-reinforced polymers (FRPs) are rapidly being introduced into a wide variety of civil engineering applications. Neale (2000) has found these materials to be particularly attractive for applications involving the strengthening and rehabilitation of existing structures. Composite materials have been proposed as a corrosion-resistant alternative to external steel reinforcement of concrete members. Iyer et al. (2000) have used sheets of graphite fibers in an epoxy matrix to strengthen cracked concrete beams in an existing bridge. Also, Saadatmanesh and Ehsani (1989) have shown that glass fiber composites, well bonded with epoxy to concrete beams, double the ultimate capacity of the beams also employed to increase strength and ductility with encouraging results in terms of mechanical behavior and cost effectiveness.

Rarely, external composite reinforcement has been applied to natural stone, as demonstrated by (Kurtis and Dharan, 1997). To determine the effect of external reinforcement on the load-carrying capacity of two types of stone, 3-point bend tests were performed on marble and Travertine marble (actually a limestone) reinforced with HS carbon fibers in an epoxy matrix. The results show how the load capacity of the stone may be increased of about 5-10 times..

The purpose of this study is to investigate a similar application of external composite reinforcement of natural stone. Such reinforcement could serve to increase low initial tensile strength or to restore strength lost by weathering. An increase in strength can result in the use of longer spans and thinner sections, decreasing dead load. Therefore, the use of external composite reinforcement of natural stone in application such as exterior cladding, flooring, countertops, and desktops can result in weight saving and possible cost saving. The differences with the work shown in (Kurtis and Dharan, 1997) are mainly three: the production of an hybrid structure “natural stone/composite” very thin, the use of less expensive composite materials, such as glass fiber, and the comparison between two natural stones that are largely used for decorative application, marble and granite. To determine the effect of external reinforcement on the strength of the two types of stone “3-point bend” and “short-beam” tests were performed.

In the following the preliminary tests used to choose the adhesive for binding stone and composite are shown; then, the tests used to mechanically characterize the stone-composite specimens are deeply discussed and their results are presented and analyzed.

II. PRELIMINARY TESTS TO CHOOSE ADHESIVE

Perlato Royal of Coreno was chosen as marble for this investigation; it is characterized by a high strength to wear and to impact that together to its resistance to weather agents have carried out to be used for buildings. Its main properties are shown in Table I. The Absolute Black was chosen as granite; it is very hard (see Table I) and since it is available in small volumes, it has a great commercial value.

Glass fiber/epoxy matrix prepreg fabric was used to reinforce the stone. The composite fabric consisted of fibers woven at [0/90]; thirteen fabrics were overlapped and cured at a temperature of 125°C for 90 minute by means of vacuum bagging in autoclave to obtain a board thick of about 2 mm; its mechanical properties are shown in Table I.

TABLE I
Properties of used materials: Stones and Glass/Epoxy Laminate

Material \ Mechanical characteristic	Density [Kg/m^3]	Compressive strength [MPa]	Tensile strength [MPa]	Flexural strength [MPa]	Elasticity Modulus [GPa]
Perlato Coreno marble	2650	166	10	5	60.8
Absolute Black granite	3030	295	27	28	40.2
S-Glass/Epoxy laminate	1850	650	1750	2150	75.5

The composite board was glued to stone by means of an adhesive. The adhesive was tested by preliminary experiments in order to verify their effectiveness for this particular application. It is commonly used for composite material and it is suitable for aerospace applications. It is an epoxy resin Scotch-Weld^{TM} EC-2216 B/A Gray of 3M^{TM}, whose polymerization time is 7 days at 24°C, 2 hours at 66°C and 30 minutes at 93°C.

To test the binding action of adhesive to keep together stone and composite, two sets of preliminary experiments were carried out. In the first one, twelve samples (six of Perlato Coreno marble and six of Absolute Black granite) of 100mm x 25mm x 22mm were produced by binding stone tiles of 100 mm x 25 mm x 20 mm with a glass board of 2 mm thickness by means of the adhesive, as shown in Fig. 1. Adhesive was applied to the unpolished surface of the stone tile that was characterized by an average roughness of 0.2 μm.

In the second one, twelve samples (six of Perlato Coreno marble and six of Absolute Black granite) of 200 mm x 40 mm x 22 mm were carried out by binding stone tiles of 200 mm x 40 mm x 20 mm with a glass board of 2 mm thickness by means of the adhesive, as shown in Fig. 2. Adhesive was applied on the raw surface of the stone tile that was characterized by an average roughness of 0.2 μm. They were tested by following the normative on stone products (UNI EN 12372). The span length used for the 3-point bend test of each sample was 150 mm. Both the tests were performed on an Instron machine by applying a tensile strength to the composite board, as shown in Fig. 2. Reinforced samples were tested at a load speed of 0.1 mm/min.

The results obtained by the two tests show that the marble/granite was broken during the tests before unsticking of the samples (see Fig. 3-4). Therefore, the adhesive was considered suitable to keep together stone and composite.

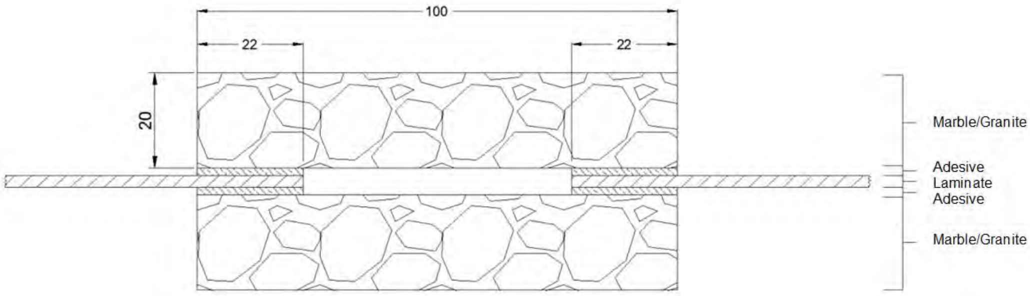


Fig. 1. Sample scheme for preliminary tensile tests.

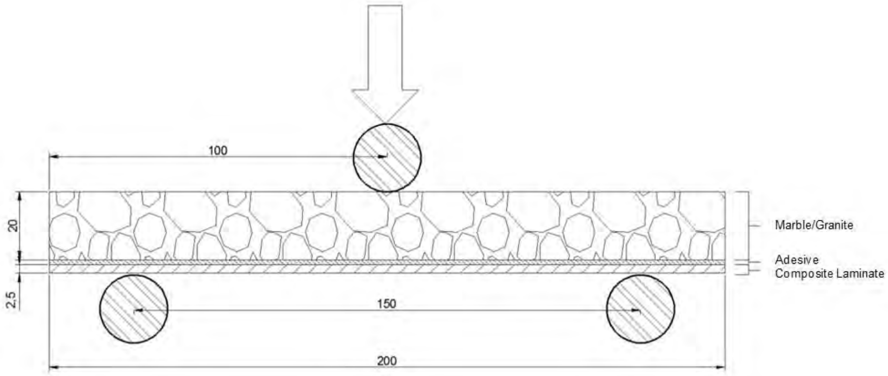


Fig. 2. Sample scheme for preliminary 3-point bend tests.

Fig. 3. Preliminary tensile tests

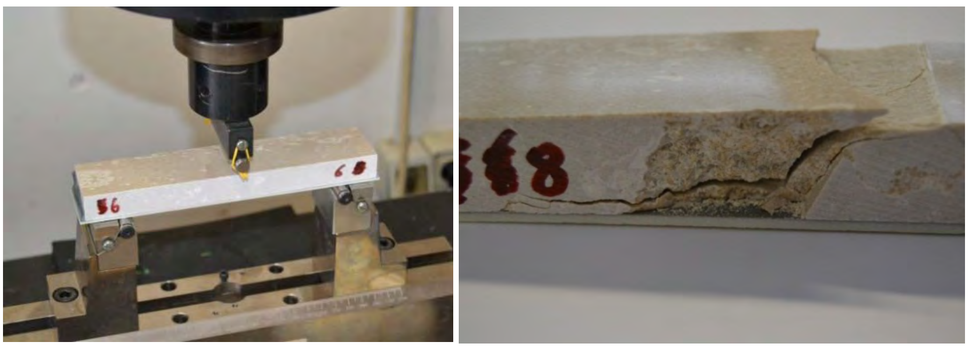


Fig. 4. Preliminary 3-point bend tests

III. EXPERIMENTAL PROCEDURE

The good results obtained by the preliminary tests carried the investigation towards the use of two different adhesive, the Scotch-Weld™ EC-2216 B/A Gray of 3M™, that was previously investigated, and the Scotch-Weld™ AF163-2k of 3M™. The second is a thermosetting epoxy resin Scotch-Weld™ AF163-2k of 3M™, which occurs as a veil. It polymerizes in 90 minutes at 107.2°C.

The two adhesives required two different processes to prepare the samples.

The obtained samples (stone with composite laminate) had a thickness of 12 mm that was reduced to 8 mm by removing the stone surface through a grader. Eight tiles, four of marble and four of granite (two for each adhesive kind), were machined still further to reduce their thickness to 6 mm. Now, each tile were cut with a diamond saw to produce samples measuring 40 mm x 200 mm for 3-point bend tests and 16 mm x 50 mm for short-beam tests. All the samples manufactured are shown in Table II.

The obtained samples were submitted to the 3-point bend test, according with the UNI EN 12372 standard for stone products, and to the short-beam test, according with the ASTM D2344 standard for composite material. In the following the processes used to prepare the samples are deeply discussed.

TABLE II
Experimental plan (Stones with Glass/Epoxy Laminate)

EXPERIMENTAL PLAN			
Stone Typology	**Adesive**	**Samples dimension [mm] - width x length x (thickness) -**	**Replications**
Perlato Coreno Marble	3M EC-2216	40x200x(4+2)*; 16x50x(4+2)**	**5**
		40x200x(6+2)*; 16x50x(6+2)**	
	3M AF163-2	40x200x(4+2)*; 16x50x(4+2)**	
		40x200x(6+2)*; 16x50x(6+2)**	
Absolute Black Granite	3M EC-2216	40x200x(4+2)*; 16x50x(4+2)**	
		40x200x(6+2)*; 16x50x(6+2)**	
	3M AF163-2	40x200x(4+2)*; 16x50x(4+2)**	
		40x200x(6+2)*; 16x50x(6+2)**	

***3-point-bend test.** (4+2): 4=Stone, 2=composite laminate; (6+2): 6=stone, 2=composite laminate

****short-beam test.** (4+2): 4=Stone, 2=composite laminate; (6+2): 6=stone, 2=composite laminate

A. Process To Prepare The Samples With EC-2216 Adhesive

Eight 200 mm x 200 mm x 10 mm lapped tiles, four of marble and four of granite, were brushed on the raw side by means of an abrasive paper and, then, they were cleaned by a cloth soaked in ethylic alcohol. The same operations were repeated on the composite laminate of 2 mm thickness, once cut through a band-saw at 205 mm x 205 mm. Now, the adhesive was applied on both the raw side of the stone and on the surface of the composite laminate with a thickness of 0.1 mm in an uniform way. Therefore, the stone was assembled to the composite and the obtained sample was put into some clamps in order to avoid the development of air bubbles and the leak of adhesive at the interface due to the excessive pressure. The samples were polymerized at room temperature for 120 minutes and at 63°C into an oven for further 120 minutes.

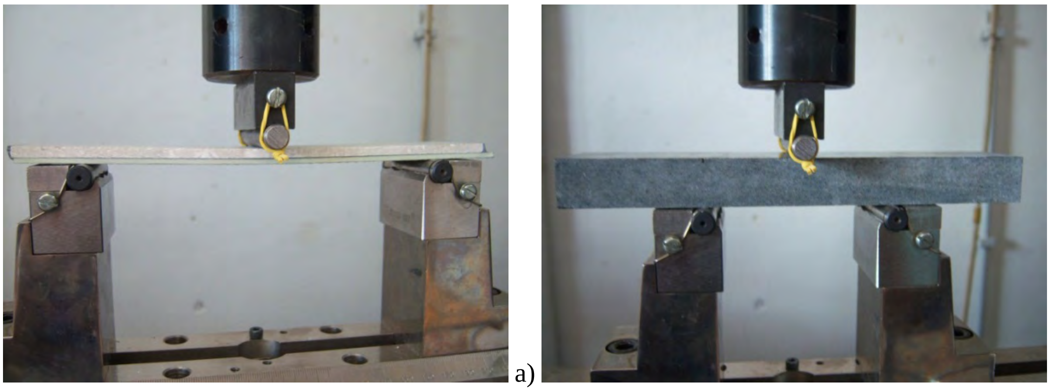
B. Process To Prepare The Samples With AF163-2K Adhesive

Eight 200 mm x 200 mm x 10 mm lapped tiles, four of marble and four of granite, were cleaned as described in the previous paragraph. The same operations were repeated on the composite laminate of 205 mm x 205 mm x 2 mm. Now, a film of adhesive was taken out the freezer and kept at room temperature for two hours. Then, it was cut at the dimensions of the tile and it was applied on the stone surface. Finally, the composite laminate was put on the other side of the adhesive film. The obtained samples were put into a vacuum bag, previously lined with breather in order to support the vacuum distribution around the samples. The bag was sealed and the air was inhaled up to a pressure of 0.50 bar. Now, the bag was put into the oven and the temperature was increased of 4.95°C per minute for twenty minutes, up to arrive at 135°C; therefore, the temperature was kept constant for 1 hour. Finally, the oven was off and the bag was kept in pressure till the temperature reached 65°C.

IV. RESULTS AND ANALYSIS

3-point bend tests were performed on a Instron machine affixed with a three-point bending configuration, see Fig. 5a-b. The span length used for the 3-point bend test of each sample was 150 mm, while the applied load was 15 MPa/min. The samples were tested in an unconditioned state at room temperature.

Both reinforced and unreinforced samples failed in a brittle shear mode and then the unsticking of the composite laminate from stone occurred.



a) b)

Fig. 5. 3-point bend test: a) Marble sample b) Granite sample.

Results from the 3-point bend tests are presented in Table III. The average maximum load for marble and granite are respectively 21.11 MPa and 40.57 MPa. The granite samples have performances better than those of marble. In particular, the samples of 4 mm thick reached an average maximum stress higher than that of samples with 6 mm thick. This is probably due to the fact that a stone tile stuck to a composite laminate shows more flexible more its thickness decreases. A further conclusion is that the AF163-2 adhesive allows to reach average maximum stress higher than that due to EC-2216 sample. Finally, results indicate that when granite is reinforced, its flexural load capacity before failure increases from 6 to 8 times; while when marble is reinforced, its flexural load capacity before failure increases from 7 to 10 times.

TABLE III
Results of 3-point bend tests (Stones with Glass/Epoxy Laminate)

3-POINT BEND TESTS			
Stone (thickness [mm])	Adhesive	Strength max [MPa]	
		Average value	Standard Deviation
Marble (4)	3M AF163-2 + Glass/Epoxy Laminate	292.58	23.63
Granite (4)		331.80	4.90
Marble (6)		235.65	2.01
Granite (6)		332.00	10.12
Marble (4)	3M EC-2216 + Glass/Epoxy Laminate	229.66	11.20
Granite (4)		314.83	3.29
Marble (6)		155.72	22.88
Granite (6)		265.00	4.85
Marble (20)	***	21.11	3.50
Granite (20)	***	40.57	5.80

Short-beam tests were performed on the same Instron machine, see Fig. 6a and 6b. Five samples of marble and five samples of granite of 40 mm x 200 mm x 20 mm were tested together with the reinforced samples. All the samples were tested at a load speed of 0.5 mm/min; while the span length used for the short-beam test of each sample was 80 mm, 24 mm and 32 mm for the unreinforced stone and the reinforced stone with a thickness of 6.2 mm and 8.2 mm respectively.

 a)  b)

Fig. 6. Short-beam test: a) Marble sample b) Granite sample.

The results from the short-beam tests are presented in Table IV. The average maximum load for marble and granite are respectively 2.35 MPa and 5.4 MPa. Results indicate that when reinforced both marble and granite experienced an order of magnitude increase in shear load capacity before failure. In particular, the granite samples have a strength higher than those in marble; the reinforced samples with a thickness of 4 mm reaches a maximum stress higher that those with a thickness of 6 mm; the adhesive AF163-2 has higher performance that EC-2216. Therefore, the highest value of the average maximum stress was reached by the granite sample of 4 mm thick and stuck with AF163-2, 41.37 MPa, while the lowest value was that of the marble sample of 6 mm thick and stuck with EC-2216, 11.41 MPa. The relatively large standard deviations can be attributed to the effects of non-uniformity within the natural stone, which can lead to variations in tested material properties.

TABLE IV
Results of short-beam tests (Stones with Glass/Epoxy Laminate)

SHORT-BEAM TESTS					
Stone (thickness [mm])	**Adhesive**	**Strength (I crack) [MPa]**		**Strength (max) [MPa]**	
		Average value	**St.Dev.***	**Average value**	**St.Dev.****
Marble (4)	3M AF163-2 + glass/epoxy laminate	9.47	4.99	20.36	7.92
Granite (4)		21.26	5.22	41.37	6.54
Marble (6)		4.37	1.15	17.00	3.12
Granite (6)		19.49	11.30	35.76	2.13
Marble (4)	3M EC-2216 + glass/epoxy laminate	3.85	3.65	22.13	3.52
Granite (4)		4.45	1.32	26.48	4.69
Marble (6)		3.10	0.66	11.42	0.97
Granite (6)		4.00	0.57	19.00	1.28
Marble (20)	***	***	***	2.35	0.45
Granite (20)	***	***	***	5.40	1.15

Fig. 7 and 8 show an example of load trend vs displacement in 3-point bend test and in short-beam test. Load/displacement curves demonstrate the effect of reinforcement on the sample deflection. Reinforced samples experienced three to six times more deflection before failure than the unreinforced stone controls.

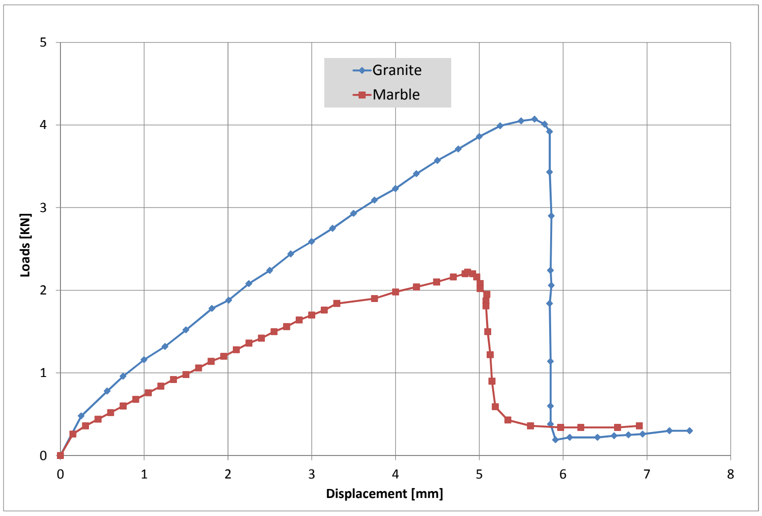


Fig. 7. Trend of Load vs Displacement in 3-point bend test: Stone 6mm+Adhesive AF163-2+ Glass/Epoxy Laminate.

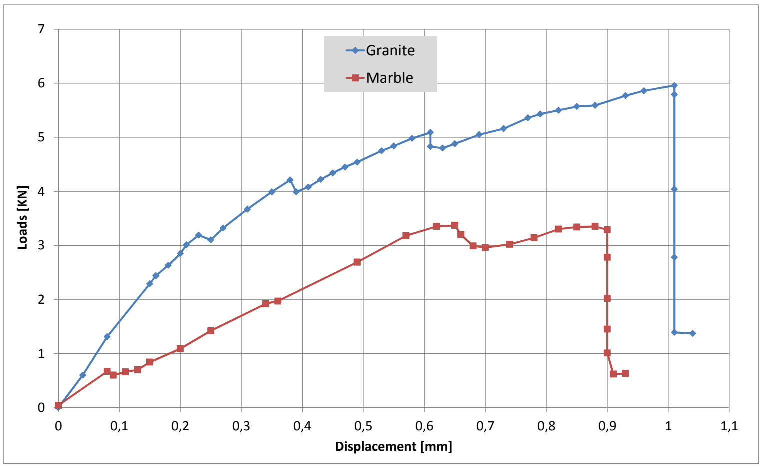


Fig. 8. Trend of Load vs Displacement in short-beam test: Stone 6mm+Adhesive AF163-2+ Glass/Epoxy Laminate.

V. CONCLUSIONS

The external composite fiber reinforcement of natural stone can be used efficiently to increase load-carrying capacity. 3-point bend tests of granite and marble reinforced with glass fiber/epoxy matrix laminates indicates that the load capacity of the stone can be increased by a factor of 8 and 7 respectively. Short-beam tests of granite and marble reinforced with glass fiber/epoxy matrix laminates indicates that the load capacity of the stone can be increased by a factor of 7 and 6 respectively. The best performances are reached by the granite samples with a thickness of 6.2 mm and stuck by AF 163-2 adhesive. The worse performances are those of marble samples with a thickness of 8.2 mm and stuck by EC-2216 adhesive. However, in all cases the external composite fiber reinforcement of natural stone allows to reduce the weight of the tile from about 70% to 78%, since it is possible to use a tile thickness of 8.2 mm or 6.2 mm instead of 20 mm.

Finally, it is possible to conclude that it is convenient to substitute tiles of natural stone of 20 mm or 30 mm thickness with thin stone tiles reinforced with glass fiber/epoxy resin. In this way it is possible to resolve some problems that are typical of stone, such as the difficulty of carriage and of assembly, the impossibility to obtain large tile (i.e. 3000 mm x 1500 mm), the excessive brittleness and so on. Moreover, it will be possible to apply the natural stone reinforced with glass fiber/ epoxy resin to nautical and aerospace field, due to the significant reduction in weight, and, therefore, it will be possible to make precious the rooms of yacht and luxurious airplanes.

Further testing should be done to determine the optimal number of composite fiber plies required to provide adequate mechanical proprieties. Such a determination could result in cost savings and increased ductility of the reinforced stone. In addition, the use of smaller thickness of stone should be investigated. Finally, an investigation of the effect of external composite reinforcement of stones that have curved shape should be conducted.

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