Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 70 (1993)

Artikel: Advanced composites for strengthening historic structures
Autor: Triantafillou, Thanasis / Fardis, Michael
DOI: https://doi.org/10.5169/seals-53344

Advanced Composites for Strengthening Historic Structures

Composites d'avant-garde pour le renforcement de structures historiques

Verbundwerkstoffe zur Verstärkung historischer Bauwerke

Thanasis TRIANTAFILLOU
Assist. Professor
Massachusetts Inst. of Technology
Cambridge, MA, USA

Th. Triantafillou, born 1963, received the Diploma in Civil Engineering (1985) from the Univ. of Patras, Greece and the MSc (1987) and PhD (1989) degrees from the Massachusetts Inst. of Technology. His research interests include the application of advanced composite materials in structures.

Michael FARDIS
Prof. of Civil Eng.
Univ. of Patras
Patras, Greece

M. Fardis, born 1949, holds an MSc and PhD from the Civil Engineering Dep. at the Massachusetts Inst. of Technology, where he served as Assistant and Associate Professor from 1979 - 1983. He is now Professor of Concrete Structures at the Univ. of Patras.

SUMMARY

The paper deals with the application of uni-directional fibre reinforced plastic (FRP) tendons for reversible strengthening of masonry monuments. The tendons, anchored to the masonry only at the ends, are circumferentially applied on the external face of the structure and post-tensioned to provide horizontal confinement. The relevant properties of FRP prestressing systems are summarised, concepts for their application in masonry structures are presented and a design procedure is proposed.

RÉSUMÉ

L'article s'occupe de l'application de câbles en fibres plastiques unidirectionnelles (FRP) dans le renforcement réversible des monuments en maçonnerie. Les câbles qui sont ancrés sur la maçonnerie à leurs extrémités seulement, sont appliqués le long du périmètre de la structure. Ensuite, ils sont tendus, afin de ceinturer horizontalement la structure. Les propriétés significatives des systèmes de précontrainte sont présentées, ainsi que les concepts de leur application. Une procédure de calcul est proposée.

ZUSAMMENFASSUNG

Der Beitrag behandelt die Verwendung von Spanngliedern aus einsinnig faserverstärktem Kunststoff für die vorübergehende Tragfähigkeitserhöhung historischer Mauerwerksbauten. Die Spannglieder werden um das Bauwerk herumgelegt, nur an ihren Enden verankert und vorgespannt, so dass sich eine horizontale Umschnürungswirkung einstellt. Die massgebenden Eigenschaften von Vorspannsystemen aus faserverstärktem Kunststoff werden kurz geschildert, Anwendungskonzepte für Mauerwerksbauten vorgestellt und Bemessungsverfahren vorgeschlagen.

1. INTRODUCTION

In recent years the importance of structural interventions in the architectural heritage (monuments, historic buildings and bridges, etc.) for repair and strengthening has increased considerably. Such interventions often follow special principles, e.g., those of the Charter of Venice (1964). Very important among these principles are the requirements that interventions should not adversely affect the *character* of the monument and must be *reversible*, especially when the techniques applied have not be proven by a very long in-service performance.

Among the methods used to upgrade historic structures are grout injections, stitching of large cracks with metallic elements or concrete zones, application of reinforced grouted perforations, external jacketing by shotcrete or by cast-in-situ concrete, and external or internal post-tensioning with steel ties [1, 2]. Unlike other methods, external post-tensioning with steel ties combines efficiency, simplicity and reversibility. It has been applied in many historic structures, such as the Rotunda and the San Andreas domes in Thessaloniki, and the Martinego rampart of the Old Castle in Corfu [2, 3], but presents some practical difficulties in protecting the strands against corrosion and handling them at the construction site (due to their considerable weight). As an alternative, the steel ties can be replaced with advanced fibre reinforced plastic composite materials, which offer excellent physical and mechanical properties, and are lightweight and immune to corrosion. Last but not least, they may be applied to historic structures in a reversible manner, in the form of external tendons in a colour matching that of the external surface of the structure.

In this paper, the authors establish the applicability of composite materials in strengthening of masonry-type monuments. The relevant properties of these materials are summarised, concepts for their application in masonry structures are presented (including attachment), and a design procedure is proposed.

2. ADVANCED COMPOSITES AS STRENGTHENING MATERIALS

Fibre reinforced plastics (FRP) have been used extensively in a variety of industries, including aerospace, automotive, ship-building and sports. They are increasingly becoming important in the construction industry too, with great potential in many areas, offering the designer an outstanding combination of properties not available from other materials. Fibres such as glass, aramid and carbon (with diameter in the range 5-25 μm) can be introduced in a certain position, volume and direction in a binding matrix (e.g., epoxy, polyester, vinylester) for maximum efficiency. When the fibres are continuous, parallel and at high volume fractions (typically more than 50%), a unidirectional material is produced with a strength and stiffness close to that of the fibres and with the chemical resistance of the matrix [4]. Among other properties, unidirectional FRPs (advanced composites) offer high strength and stiffness, lightness and immunity to corrosion. Therefore, use of these materials for special applications in construction is highly attractive and cost effective, due to improved durability, reduced life-cycle maintenance costs, savings from easier transportation and improved on-site productivity.

Because of their advantages over conventional materials (low and high strength steels), unidirectional FRPs have found their way in numerous construction applications, including: (a) development of tendons for prestressing [5-11]; and (b) strengthening of concrete and wood structures with non-prestressed or prestressed composite sheets, bonded externally on the tension faces using epoxy adhesives [12-17]. In all these applications, the composites are manufactured by highly automated processes such as pultrusion, in which fibres are pulled through a heated die into which resin is injected, and a fully cured element is produced with good dimensional stability.

The concept proposed here for the application of advanced composites as strengthening materials of masonry-type historic structures involves the introduction of circumferential externally attached ties, post-tensioned on horizontal planes. There is quite a large number of FRP materials manufacturers and suppliers around the world, and several companies provide complete tendon-anchorage systems. From a variety of products, basic information (including physical properties) about the most widely known commercial systems is given in Table 1, and a comparison of the mechanical properties of these systems is given in Table 2 [5-11, 18].

Table 1 Representative tendon-anchorage FRP post-tensioning systems.

Manufacturer	Product name	Shape	Fibre, matrix	Fibre volume fraction, V_f	Density, ρ (kg/m^3)	Coeff. of thermal expansion, α ($x10^{-6}/^oC$)
Bayer AG & Strabag Bau AG (Germany)	Polystal	Round	E-Glass, polyester	0.68	2000	7.0
ICI Linear Composites Ltd.(England)	Parafil G	Rope	Aramid (Kevlar 49)	1.00	1400	-5.7
HBG & AKZO (Holland)	Arapree	Both round & strip	Aramid (Twaron), epoxy	0.44	1400	-1.8
Mitsui Constr. Co. (Japan)	FiBRA	Round	Aramid (Kevlar 49), epoxy [1]	0.65	1300	
Teijin Co. & Sumitomo Constr. Co. (Japan)	Teijin Rod	Round	Aramid (Technora), vinylester	0.65	1300	
Tokyo Rope Mfg Co. & Toho Rayon Inc. (Jap.)	CFCC	Multi-wire cables	Carbon (Besfight), epoxy	0.60	1500	0.6
Mitsubishi Kasei Co. (Japan)	Leadline	Round	Carbon (Dialead), epoxy	0.65	1600	

[1] Braided Aramid, impregnated with epoxy

Polymeric composites are often subjected to environmental effects such as attack by chemicals, moisture uptake, temperature fluctuations and irradiation with ultra-violet light (UV), which may lead to deterioration and premature failure. In general, carbon fibre reinforced plastic (CFRP) is highly resistant to these effects, glass fibre reinforced plastic (GFRP) is sensitive, while aramid fibre reinforced plastic (AFRP) displays an intermediate behaviour. The detrimental action of moisture and chemicals (e.g., alkalis) to GFRP and that of UV to AFRP deserve special mention. Finally, it is worth mentioning that in some of the prestressing systems above the rods are protected: in Polystal, a 0.5 mm polyamide coating is employed; in Parafil G, the continous fibres are contained within a thermoplastic sheath (protected from UV); and in CFCC the wires are overwrapped with a polymeric yarn.

3. CONCEPTS AND ANCHORAGE

Masonry structures can be consolidated and strengthened using FRP ties as illustrated in Figure 1. The tendons, in the form of either round rods or strips attached to the masonry only at their ends, are circumferentially applied on the external face of the structure and post-tensioned to provide horizontal confinement.

Table 2 Mechanical properties of various post-tensioning elements (according to manufacturers).

Product	Young's modulus, E (GPa)	Tensile strength, $f_{FRP,t}$ (GPa)	Ultim. strain, ϵ_u (%)	Poisson's ratio, ν (-)	Creep / elastic strain	Relaxation (%)	Stress rupture[2]
Polystal	51	1.57	3.3	0.27	0.03 (2 yrs)	1.4 (100 hrs) 3.5 (100 yrs)	0.70[3]
Parafil G	120	1.95	1.6		0.04 (1 day)	4.0 (100 hrs) 8.0 (100 yrs)	0.40
Arapree	55	1.35	2.4	0.38	0.002[1] (100 yrs)	7.5 (100 hrs) 15 (100 yrs)	0.60
FiBRA	64	1.35	2.2	0.62		10 (100 hrs) 20 (100 yrs)	
Teijin	55	1.90	3.6	0.35		8 (100 hrs) 20 (100 yrs)	
CFCC	137	1.80	1.6		0.0004 (100 hrs, 180 °C)	1 (100 hrs)	
Leadline	147	1.80	1.3				

1 This value appears to be too low for AFRP, which is known to creep considerably more than GFRP and CFRP

2 Projected residual strength as a fraction of the short-term strength, after stressing the elements at about $0.5f_{FRP,t}$ for 100 yrs (and testing after unloading)

3 This value appears to be too high for glass/polyester, which displays very poor stress rupture behaviour

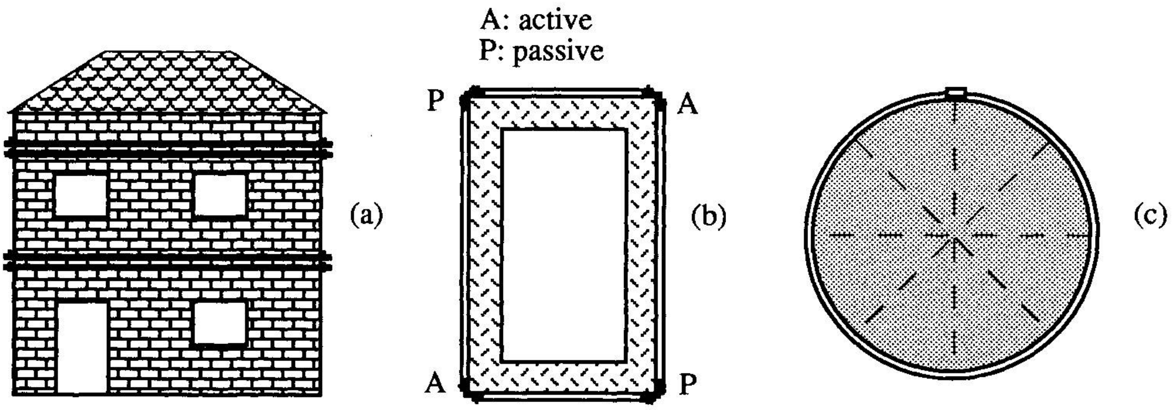

Fig. 1 Application of external FRP ties: (a) elevation; (b) plan view of rectangular structure; and (c) plan view of spherical dome.

Due to their anisotropic nature, unidirectional composites have relatively low transverse compressive strength (approx. $0.1f_{FRP,t}$) and even lower (interlaminar) shear strength. Furthermore, because of their brittle nature, the materials are sensitive to stress concentrations and hence cannot be pierced or threaded. Finally, their abrasion resistance allows only limited frictional stresses. Thus, conventional anchoring solutions (upset heads, threads, wedges, etc.) are not applicable, and relatively large anchor lengths are required. Strip-like tendons may be better than round ones for external post-tensioning of masonry, because they minimize anchor lengths (due to their large surface area) and simplify the attachment of anchorages on the masonry walls. Proposed concepts for anchorages and their attachment on masonry are illustrated in Fig. 2.

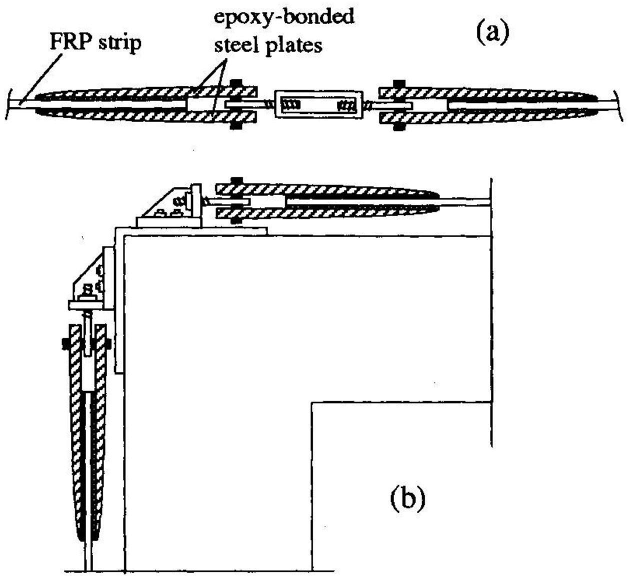

Fig. 2 Conceptual FRP anchorage/attachment for (a) circumferential prestressing of circular domes; and (b) masonry structure corners.

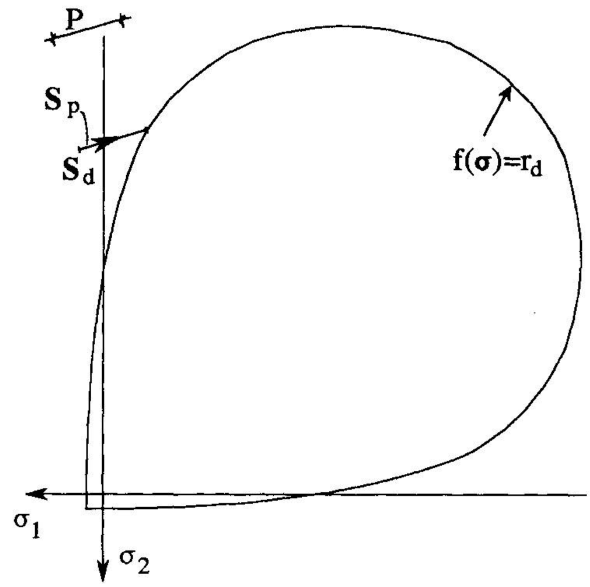

Fig. 3 Illustration of design procedure.

Figure 2(a) refers to circumferential prestressing of structures with a circular plan and involves a single FRP tendon around the perimeter, gripped at each end between a pair of steel plates to which it is epoxy-bonded. The two pairs of plates extend into a corresponding threaded steel bar and are coupled by a usual threaded bar coupler. Because FRP tendons cannot be bent to a large curvature, they cannot turn around sharp corners of the structure and have to be individually anchored there. For this latter case the anchorage in Fig. 2(b) is proposed herein, involving a structural steel angle weakly attached to the corner of the wall and transferring prestressing forces to the masonry through bearing stresses. The two tendons anchored at the same corner angle have to be prestressed gradually, by alternate turning of the nuts at their end anchorage, so that at each corner the moments of the individual tendon forces with respect to the corresponding wall mid-surface counterbalance each other. For no such end moment to develop during tensioning at a dead or passive anchorage (P in Fig. 1(b)), the two pairs of tendons actively anchored at two diametrically opposite corners (A in Fig. 1(b)) have to be tensioned simultaneously.

4. DESIGN PROCEDURE

Considering that at the generic point **x** of the structure the masonry is in a biaxial state of stress, the strengthening effect of circumferential prestressing by FRP is due to the in-principle beneficial effect of introducing additional compression to each normal stress component. If the ultimate strength condition of the masonry, shown in Fig. 3 in biaxial principal stress space for the case of isotropic stone-masonry, is expressed as:

$$f(\sigma(\mathbf{x}))-r(\mathbf{x})=0 \qquad (1)$$

in which for biaxial stresses σ stands for (σ_1, σ_2), or, in general, for $(\sigma_x, \sigma_y, \tau_{xy})$ for anisotropic (e.g. brick) masonry, then the design ultimate limit state under biaxial stresses is given by:

$$f(\sigma(\mathbf{x}))-r_d(\mathbf{x})\equiv f(\sigma(\mathbf{x}))-\frac{r(\mathbf{x})}{\gamma_m}=0 \qquad (2)$$

In Eqs. (1) and (2) the "constant" r(**x**) of the ultimate strength condition is a measure of the as-built strength of the masonry, e.g. its uniaxial compressive strength in the horizontal or in the vertical direction, and depends, in general, on location **x**. γ_m in Eq. (2) is the material partial safety factor for the old masonry, which may be different than the one for new masonry (its value may be taken higher, depending on the historical importance of the structure, or lower, due to better knowledge of the as-built strength properties).

The ultimate strength condition of isotropic masonry can be fitted by the failure criterion proposed by Ottosen [19] for concrete:

$$\alpha J_2 + \lambda\sqrt{J_2} + \beta I_1 = 1 \tag{3}$$

in which I_1 is the first stress invariant, J_2 is the second deviatoric stress invariant and

$$\lambda = c_1 \cos\frac{\cos^{-1}(c_2 \cos 3\theta)}{3} \qquad \text{if} \qquad \cos 3\theta \geq 0 \tag{4a}$$

$$\lambda = c_1 \cos\left(\frac{\pi - \cos^{-1}(-c_2 \cos 3\theta)}{3}\right) \qquad \text{if} \qquad \cos 3\theta < 0 \tag{4b}$$

In Eqs. (4a, b) $\cos 3\theta = 3\sqrt{3}J_3 / 2J_2$, with J_3 the third deviatoric stress invariant. To fit biaxial test data for stone masonry with a ratio of uniaxial strengths in tension and compression equal to 0.085 and of equal biaxial to uniaxial compression strength ratio equal to 1.65, the following parameter values can be used: $\alpha = 0.665 / f_m^2$, $\beta=3.84/f_m$, $c_1=13.8/f_m$ and $c_2=0.959/f_m$ (f_m=uniaxial compressive strength). For anisotropic (brick) masonry, the models by Ganz and Thuerliman [20] including tensile strength of bed joints, or by Koenig et al [21] or Dialer [22] may be used.

The state of stress in Eqs. (1) and (2) equals:

$$\sigma(\mathbf{x}) = S_d(\mathbf{x}) + \sum_{i=1,n_p} P_i\, S_{pi}(\mathbf{x}) \tag{5}$$

in which $S_d(\mathbf{x})$ is the value of $\sigma(\mathbf{x})$ due to the ultimate limit state design combination of actions, factored with the appropriate load partial safety factors, γ_F, and combination factors, ψ_o. P_i is the uknown value of the prestressing force of FRP tendon or group of tendons i and $S_{pi}(\mathbf{x})$ the state of stress at **x** due to P_i=1, and n_p the number of tendons or groups of tendons with independently different and unknown prestress force values. For simple geometries, such as rectangular in plan structures or spherical domes, analytical expressions for the stresses $S_d(\mathbf{x})$ and $S_{pi}(\mathbf{x})$ can be obtained, while for complicated three-dimensional structures with openings, finite element analyses will be required.

The n_p unknown prestressing forces are determined by satisfying the nonlinear in these values design ultimate limit state condition, Eq. (2), at n_p representative locations **x**. Alternatively, we may seek to minimise a linear functional of P_i, which expresses the total cost of prestressing, subject to the nonlinear constraints $f(\sigma(\mathbf{x}))-r_d(\mathbf{x})\leq 0$ at more than n_p locations **x**. Usually in good approximation the state of stress within an area of the structure is affected only by the value P of the prestressing force of a single group of FRP tendons, typically located within the same area:

$$\sigma(\mathbf{x}) \approx S_d(\mathbf{x}) + P\, S_p(\mathbf{x}) \tag{6}$$

The meaning of the combination of Eqs. (2) and (6) is shown in Fig. 3. P is the distance of the stress point $S_d(\mathbf{x})$ due to the design actions from the design ultimate limit state, Eq. (2), measured along the direction defined by the stress vector $S_p(\mathbf{x})$ through the point $S_d(\mathbf{x})$. This problem has a solution only if the arrangement of the tendons is such that the line through $S_d(\mathbf{x})$ along the direction of $S_p(\mathbf{x})$ intersects the design ultimate limit state, Eq. (2).

Once the values of the P_i have been determined, the cross-sections of the tendons are computed on the basis of the FRP design strength, $f_{FRP,d}=f_{FRP,t}/\gamma_{FRP}$. The value of the partial safety factor γ_{FRP} depends on the dispersion of the FRP strength (typical coefficient of variation 2-5%), and the ratio between its mean and characteristic values, taking into consideration the consequences of its (brittle) failure. For the design of the anchorage by epoxy-bonding to the steel plates, the ratio of the anchorage length to the thickness of the FRP strip should (roughly speaking) not be less than one-half the ratio between the design strength values of the FRP in tension and the epoxy in shear. Finally, for the anchorage detail of Fig. 1(b), the bearing strength of the masonry should be checked, taking into account the beneficial effect of stress triaxiality under the contact plates.

5. CONCLUSIONS

Fibre reinforced plastics offer many advantages as strengthening materials of historic structures: they have excellent physical and mechanical properties, are lightweight and immune to corrosion, and may be applied in a reversible manner in the form of circumferential externally attached tendons in a colour matching that of the external surface of the structure. Concepts for the application and attachment of post-tensioned FRP ties are developed, along the lines of providing horizontal confinement to masonry structures and minimising anchor lengths. The design of the strengthening scheme can be accomplished on the basis of the general design procedure proposed here, which is applicable to any type of masonry structure and material.

6. ACKNOWLEDGEMENT

The Hellenic Secretariat for Research and Technology is financially supporting this work.

REFERENCES

1. CESTELLI-GUIDI C., Strengthening of Building Structures - Therapy. IABSE Symp. on *Strengthening of Building Structures - Diagnosis and Therapy*, Venezia 1983, Introductory Report, **45**, 81-114.

2. United Nations Development Program / United Nations Industrial Development Organization, *Building Construction under Seismic Conditions in the Balkan Region, Vol. 6: Repair and Strengthening of Historical Monuments and Buildings in Urban Nuclei.* UNDP/UNIDO Proj. RER/79/015, J. G. Bouwkamp, Chief Techn. Advisor, Vienna 1984.

3. MILTIADOU A. and DELINICOLA E., Earthquake Resistant Preventive Measures to Consolidate a Historical Rampart. *Proc. 8th Europ. Conf. on Earthq. Engrg.*, **11.2**, 41-48, Lisbon 1986.

4. HULL D., *An Introduction to Composite Materials.* Cambridge Univ. Press, Cambridge, England, 1981.

5. PREIS L. and BELL T. A., Fiberglass Tendons for Posttensioning Concrete Bridges. *TRR 1118*, NRC, Washington D.C. 1986, 77-82.

6. Imperial College of Science and Technology, *Symp. on Engrg. Appl. of Parafil Ropes*, London 1988.

7. TANIGAKI M., OKAMOTO T., TAMURA T., MATSUBARA S. and NOMURA S., Study of Braided Aramid Fiber Rods for Reinforcing Concrete. *13th IABSE Congress*, Helsinki 1988, 15-20.

8. GERRITSE A. and WERNER J., Arapree, a Non-metallic Tendon. ASCE Spec. Conf. on *Advanced Composite Materials in Civil Engineering Structures*, Las Vegas 1991, 143-154.

9. KAKIHARA R., KAMIYOSHI M., KUMAGAI S. and NORITAKE K., A New Aramid Rod for the Reinforcement of Prestressed Concrete Structures. ASCE Spec. Conf. on *Advanced Composite Materials in Civil Engineering Structures*, Las Vegas 1991, 132-142.

10. ZOCH P., KIMURA H., IWASAKI T. and HEYM M., Carbon Fiber Composite Cables - A New Class of Prestressing Members. *70th TRB Annual Meeting*, Washington D.C. 1991.

11. KOGA M., OKANO M., SAKAI H., KAWAMOTO Y. and YAGI K., Application of a Tendon made of CFRP Rods to a Post-tensioned Prestressed Concrete Bridge. 1st Intern. Conf. on *Advanced Composite Materials in Bridges and Structures*, Sherbrooke 1992, Canada, 405-414.

12. MEIER U., Bridge Repair with High Performance Composite Materials. *Material & Technik*, **4**, 125-128, 1987.

13. TRIANTAFILLOU T. C. and DESKOVIC N., Innovative Prestressing with FRP Sheets: Mechanics of Short-term Behavior. *ASCE J. Engrg. Mech.*, **117**(7), 1652-1672, 1991.

14. MEIER U., DEURING M., MEIER H. and SCHWEGLER G., Strengthening of Structures with CFRP Laminates: Research and Applications in Switzerland. 1st Intern. Conf. on *Advanced Composite Materials in Bridges and Structures*, Sherbrooke, Canada 1992, 243-251.

15. PLEVRIS N. and TRIANTAFILLOU T. C., FRP-reinforced Wood as Structural Material. *ASCE J. Mater. Civ. Engrg.*, **4**(3), 300-317, 1992.

16. ROSTASY F. S., HANKERS C. and RANISCH E.-H., Strengthening of R/C - and P/C - Structures with Bonded FRP Plates. 1st Intern. Conf. on *Advanced Composite Materials in Bridges and Structures*, Sherbrooke, Canada 1992, 253-263.

17. TRIANTAFILLOU T. C. and PLEVRIS N., Strengthening of RC Beams with Epoxy-bonded Fibre-composite Materials. *Mater. and Struct.*, **25**, 201-211, 1992.

18. MUFTI A. A., ERKI M.-A. and JAEGER L. G., eds,. *Advanced Composite Materials in Bridges and Structures in Japan.* Can. Soc. Civ. Engrg., Task Force Report, 1992.

19. OTTOSEN N., A Failure Criterion for Concrete. *ASCE J. Engrg. Mech.*, **103**(4), 527-535, 1977.

20. GANZ H. R. and THUERLIMAN B., Design of Masonry Walls under Normal Force and Shear. *Proc. 8th Int. Brick/Block Masonry Conf.*, Dublin, Ireland 1988, 1447-1457.

21. KOENIG G., MANN W. and OETES A., Untersuchungen zum Verhalten von Mauerwarksbauten unter Erdbeben eienwirkung. Koenig und Heunisch, Frankfurt, Okt. 1988.

22. DIALER C., Some Remarks on the Strength and Deformation Behavior of Shear Stressed Masonry Panels under Static Monotonic Loading. *Proc. 9th Int. Brick/Block Masonry Conf.*, Berlin, Germany 1991, 276-283.