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Strengthening of Square RC Columns using Externally Bonded FRP Sheets

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***Abstract*— An experimental study is presented in this paper on the behaviour of square R. C. columns of size 750 × 150 × 150 mm retrofitted with Glass fibre reinforced polymer (GFRP) sheets along with a brief review of literature. One column without GFRP and four columns complete wrapped with one, two, three and four layers of GFRP sheets have been tested for axial loading. The failure axial loads and failure modes of the columns have also been observed. A critical discussion is made with respect to increase in the strength of retrofitted columns with respect to the column without GFRP in order to explore the optimal use of GFRP for strengthening the R. C. columns. Further, an analytical model of RC column retrofitted with externally bonded FRP has also been proposed in compatibility with IS: 456-2000 [1] as the design guidelines on strengthening/retrofitting of concrete structures using externally bonded FRP laminates/sheets are yet to be recommended in India. The experimental ultimate load carrying capacity of columns is also compared with that of the respective columns predicted from the present analytical model and literature.**

***Keywords*— RC columns, FRP, GFRP, strengthening, retrofitting, axial strength**

I. Introduction

The major problem faced by civil engineers worldwide is premature deterioration in concrete structures. The deterioration is mainly due to environmental effects, which includes corrosion of steel, gradual loss of strength with ageing, repeated high intensity loading, variation in temperature, freeze-thaw cycles, contact with chemicals and saline water and exposure to ultra-violet radiations. This problem, coupled with revisions in structural codes needed to account for the natural phenomena like earthquakes or environmental deteriorating forces, demands development of successful structural retrofit technologies. Retrofitting of concrete structures with wrapping of FRP sheets provide a more economical and technically superior alternative to the traditional technique used in many situation, because it offers high strength, low weight, corrosion resistant, high fatigue resistant, easy and rapid installation and minimal change in structural geometry.

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A large number of experimental investigations have been carried out on circular concrete columns confined with fibre reinforced polymer (FRP) composite sheets to study the various parameters such as strength, ductility, effect of confinement and presence of internal reinforcement. The most of the above work was focused on behaviour of FRP confined concrete columns with normal strength concrete [2-5]. Wu et al. [6] and Cui and Sheikh [7] conducted experimental study on FRP confined concrete columns with high strength concrete. Moreover, the behaviour of full scale FRP confined concrete circular columns under axial load was investigated and reported in the literature [8-10]. The experimental results demonstrated that there were clear difference in the axial stress-strain behaviour between FRP confined concrete columns of smaller and larger size. In addition, experimental studies have also been conducted on FRP confined RC square and rectangular concrete columns and reported in the literature [5, 11-18]. It has been widely recognized that the lateral pressure provided by the FRP jacket is not uniform along the cross sectional perimeter. It is high in the proximity of corners and low along the sides and hence the cross section is only partially confined.

Several analytical models have been proposed to describe the behaviour of FRP confined concrete circular columns [11, 19-25]. These models calculate the axial stress and axial strain of FRP confined concrete at a given lateral strain by using an active confinement model for concrete. Similarly, in order to predict the peak axial stress for square and rectangular FRP confined concrete columns, a number of theoretical models have also been developed and reported in the literature [15, 26-32]. However, their predictive equations do not converge to the same values and their validity for full scale columns still has to be proven. Moreover, Pellegrino and Modena [33] has presented an analytical model for FRP confinement of circular and rectangular columns with and without internal steel reinforcement and validated the same with some available results.

It is worth mentioning that while no country yet has any national code, several national guidelines [34-38] offer the state of the art in selection of FRP systems and design and detailing of structures incorporating FRP composites. However, there exists a divergence of opinion about certain aspects of the detailing between the guidelines.

From the review of the above literature, it is clear that the behaviour of FRP jacketed circular concrete columns is not same that of FRP jacketed square or rectangular columns as the confined pressure is not uniform along the perimeter of square/rectangular columns like circular ones. The results obtained from experimental investigation and proposed analytical models, particularly for square/rectangular columns, are not converging to the same values in many respects.

To address the knowledge gaps identified as above, this paper presents an experimental investigation on GFRP jacketed square reinforced concrete columns of larger size subjected to axial loads by varying the number of layer of GFRP sheets. Moreover, an attempt has also been made to propose an analytical model for RC columns retrofitted with externally bonded FRP in compatibility with IS: 456-2000 [1]. Further, the axial load carrying capacity of columns retrofitted with GFRP sheets obtained from the experimental investigation is compared with that predicted from the present model and ACI-440.2R-02 [34] along with a critical discussion.

II. Experimental Investigation

In order to study the structural performance of retrofitted R. C. square columns with GFRP, five columns are casted, out of which, only one without GFRP and the remaining four columns externally bonded with GFRP are tested under pure axial loading. Details of testing of GFRP, casting of test specimens, wrapping of GRFP sheet on test specimens, experimental set up, testing and observation and results and discussions are presented in the following sub-heads.

A. *Testing of GFRP*

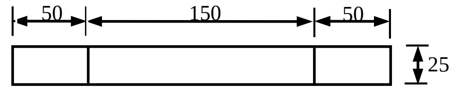
GFRP sheet used here is a fabric of 0.275 mm thick and is made up by stitching cross glass fibres. For testing the material properties of GFRP fabric sheet, four coupons were prepared by binding four layers of sheets with binding materials as shown in Fig.1. The binding materials used were Epoxy (CY230) and Hardener (HY951). The above were mixed in the ratio (9:1) and used to bind the FRP. The above four coupons were tested after being cured properly and various parameters like Young's modulus, % strain at 0.2% yield, stress at 0.2% yield, load at break and load at peak were obtained. The average values of the parameters, such as load at peak, load at break, percentage of strain at 0.2% yield, stress at 0.2% yield and Young' modulus are 7.280 kN, 6.442 kN, 1.231%, 101.40 MPa, and 9825 MPa, respectively.

B. *Casting of test specimens*

For conducting experimental investigation, five square reinforced concrete column specimens of size (150 mm × 150 mm × 750 mm) were casted with M35 grade concrete and Fe 415 grade steel. Three concrete cubes of size 150 mm are casted along with the casting of each column. The columns and cubes are allowed for 28 days curing in water. The column with dimensions and reinforcement detailing is shown in Fig.2.

C. *Testing and observation*

The column specimens have been tested in the Universal Testing Machine (UTM-1000 kN) under uniformly increasing axial loading. The load at which the first visible crack/tearing in GFRP sheet has been observed is recorded as cracking load. Then the load has been applied till the ultimate failure of the column. A load versus displacement graph was shown on the screen of the computer during the testing and it was recorded. The complete test set up in UTM is furnished in Fig.3.



(a) Top view

(b) Coupons prepared from GFRP sheets for testing
All dimensions are in mm

Figure 1. Details of GFRP coupons

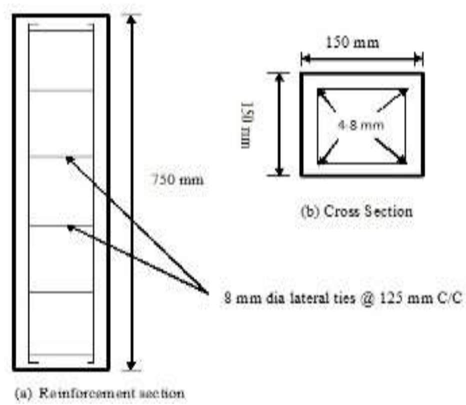


Figure 2. Dimension and reinforcement details of R.C. column

Figure 3. Complete test set up in UTM

During testing it has been observed that all the five columns tested have shown almost similar behavior in the initial stage of loading. In the case of column C1 (without GFRP), the first hair crack has occurred at the bottom of the column with the load of 170 kN. When axial compressive strain increases due to increase of axial load, lateral tensile strain also increases. Therefore, appreciable tensile cracks have been occurred in the top portion of the column at a load of 508 kN as concrete is very weak in tension. Finally, the splitting failure of concrete has occurred at an ultimate load of 515 kN with displacement of 4.5mm. The failure of column C1 is shown in Fig. 4 (a). In the column C2 (with 1 layer of GFRP), the first crack has occurred at the top of the column at a load of 400 kN with tearing of GFRP sheet and splitting of concrete due to lateral tension. Then the failure has occurred at a load of 527.85 kN with displacement of 5.8mm with the

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tearing of GFRP sheet from top of the column to the middle portion and splitting of concrete. Maximum displacement of 8.6 mm has been observed at a load of 316.70 kN when the complete failure occurred as shown in Fig. 4 (b). The column C3 (with 2 layers of GFRP) has shown almost similar behavior as in case of C1 with tearing of GFRP sheet and splitting failure at 642.75 kN. Maximum displacement of 6.7 mm has been noticed at a load of 385.66 kN when complete failure has occurred. In this case, the splitting of concrete in the top portion of the column has been observed due to lateral tension and GRFP sheets have been torn as indicated in Fig. 4 (c). Column C4 (with 3 layers of GFRP) has shown the similar trend with tearing of GFRP sheets and splitting of concrete in the top portion of the column at the failure load of 700.45 kN due to lateral tension. The failure of column C4 is shown in Fig. 4 (d). In column C5 (with 4 layer of GFRP), debonding has occurred at the bottom portion at a load of 470 kN unlike previous cases. The crushing of concrete has started at the load of 600 kN at the bottom portion of the column due to increase in bearing pressure and consequently tearing of the GFRP sheets. Failure has occurred at a load of 616.80 kN with further crushing of concrete and tearing of the GFRP in vertical direction as shown in Fig. 4 (e).

The load versus displacement curves for all the above columns obtained from the UTM are shown in Fig 5. From Fig. 5, it is observed that maximum displacements are 5.8 mm, 8.6 mm, 6.7 mm, 11.8 mm and 13.1 mm for Columns C1, C2, C3, C4 and C5, respectively, indicating not only enhancement of axial strength, but also enhancement of ductility.

D. *Experimental results and discussions*

The various test results of columns, such as compressive strength of cubes, cracking load and ultimate load, along with percentage of increase in axial strength due to retrofitting of GFRP sheets are presented in Table 1.

From Table 1, it is evident that the strength of columns has been increased by retrofitting them with GFRP sheets. The strength of columns increases with the increase in the number of layers of GFRP sheets up to 3 and then decreases. The enhancement of strength has been observed as 2.5%, 24.8%, 36% and 19.8% for columns retrofitted with 1, 2, 3 and 4 layers of GFRP sheets, respectively. It is observed that if number of layers increases, there is chance of debonding between concrete and GFRP sheets and failure mode may change from splitting of concrete and tearing of GFRP sheets to crushing of concrete due to bearing failure and consequently tearing of GFRP sheets. Due to above reason, the failure load may decrease even if the number of layer of GFRP sheet increases. Hence, it is clear that the maximum strength can be obtained with optimum number of layers of GFRP sheets.

III. Theoretical Investigation

An analytical model of RC column retrofitted with externally bonded FRP has been proposed in compatibility with IS: 456-2000 [1], which is presented in the following sub section.

(a) Column C1 (b) Column C2
(c) Column C3 (d) Column C4 (e) Column C5

Figure 4. Failure of different columns

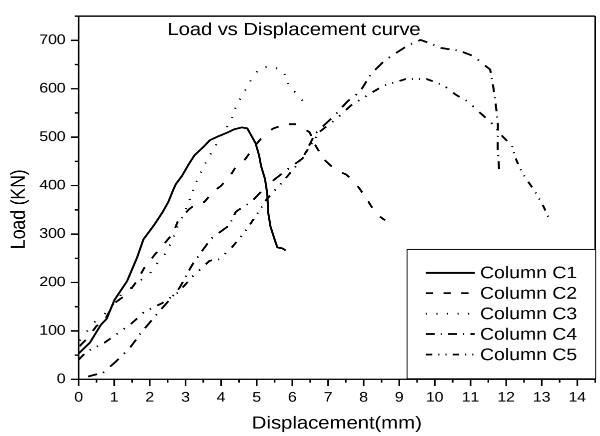

Figure 5. Load vs, Displacement curves of columns

TABLE 1. TEST RESULTS OF COLUMNS WITH/WITHOUT GFRP

Sl. No.	Column	Compressive strength of cubes (N/mm^2)	Cracking/ tearing load (kN)	Ultimate load (kN)	Increase in ultimate load with reference to C1 (%)
1.	C1	34.67	170.00	515.00	0.0
2.	C2	36.29	380.00	527.85	2.5
3.	C3	36.59	428.00	642.75	24.8
4.	C4	35.55	480.00	700.45	36.0
5.	C5	35.41	470.00	616.80	19.8

A. *Mathematical formulation*

In this model, the confinement pressure has been ignored as it is reported in the literature that the rectangular/square columns retrofitted with FRP sheets are partially confined. In addition to the assumptions considered in the literature [1], it is further assumed that the strain compatibility is maintained at the interface of the FRP sheets, i.e. there is no slip between FRP sheets and concrete.

When FRP sheets are wrapped around four side of the rectangular RC column, the equations for the axial load are obtained as follows:

$$P_u = 0.4 f_{ck} bD + (\sigma_{sc} - \sigma_{cc}) A_{sc} + \sigma_f A_f \quad (1)$$

$$P_u = 0.4 f_{ck} bD + (\sigma_{sc} - 0.4 f_{ck}) A_{sc} + 0.004 E_f (b + D) t_f \quad (2)$$

Where, P_u is ultimate axial compressive strength of column; f_{ck} is characteristic stress of concrete; b and D are width and depth of the column, respectively; σ_{cc}, σ_{sc} and σ_f are design compressive stress in concrete, steel and GFRP corresponding to the strain equal to 0.002, respectively; A_{sc} and A_f are cross sectional areas of steel and fibre, respectively; t_f and E_f are thickness and modulus of elasticity of fibre, respectively.

B. *Analytical results and discussions*

The theoretical ultimate axial strength of each column is calculated from the present model as well from ACI-440.2R.02 [34] and presented in Table 2 along with the experimental results. It is observed that theoretical values predicted from both the models are less than experimental ones, which is expected. However, it is clear from the table that both the models yield the conservative results. The percentage increase in strength of columns wrapped with GFRP sheets with respect to the respective control columns (columns without wrapping of GFRP sheet) is indicated in parentheses in Table 2. It is observed that the percentage increase in strength of columns due to wrapping of layers of GFRP in experimental results is much more in comparison to that in both the analytical models. The maximum percentage of increase in strength is 36.0% for wrapping of three layers of GFRP sheets for experimental case where as the same is only 3.6% and 2.0% with four layers of GFRP sheets for present model and the model developed as per ACI-440.2R.02 [34], respectively. Therefore, both the models have to be more refined for achieving improved results which can be comparable with the experimental results.

TABLE 2. COMPARISON BETWEEN ULTIMATE AXIAL STRENGTH OBTAINED FROM EXPERIMENT AND FROM ANALYTICAL MODELS

Sl. No.	Column	$P_{u,exp}$* (kN)	$P_{u1,th}$** (kN)	$P_{u2,th}$*** (kN)	$P_{u1,th}/P_{u,exp}$	$P_{u2,th}/P_{u,exp}$
1.	C1	515.00 (0.0)	367.81 (0.0)	490.99 (0.0)	0.714	0.953
2.	C2	527.85 (2.5)	371.05 (0.9)	493.54 (0.5)	0.703	0.935
3.	C3	642.75 (24.8)	374.29 (1.8)	496.09 (1.0)	0.582	0.770
4.	C4	700.45 (36.0)	377.53 (2.7)	498.63 (1.5)	0.539	0.712
5.	C5	616.80 (19.8)	380.77 (3.6)	501.18 (2.0)	0.617	0.812

* Ultimate experimental axial strength of columns

** Ultimate theoretical axial strength of columns predicted from the present model

*** Ultimate theoretical axial strength of columns predicted from ACI-440.2R.02 [34]

IV. Conclusions

Based on the experimental and analytical results, the following conclusions are drawn from the present study:

1. The axial strengthening of RC columns can be made effectively using externally bonded FRP sheets/fabrics/laminates. In this study, the strength has been enhanced up to 36% with retrofitting of only 3 layers of GFRP sheets.
2. The axial strength of RC column retrofitted with GFRP sheets increases with increase in number of layer initially up to certain number of layer, then decreases with further increase in number of layer of GFRP sheets. Hence, the maximum strength can be obtained with only optimum number of layers of GFRP sheets.
3. The failure mode changes with increase in number of layers of GFRP sheets beyond optimum number from tearing of GFRP sheets and splitting of concrete in the top portion of column due to lateral tension to crushing of concrete and tearing of GFRP sheets in the bottom portion of column due to bearing pressure. This finding may be verified with further testing of more number of columns retrofitted with different layer of GFRP sheets.
4. The present model developed in accordance with IS: 456-2000 [1] and the model developed in accordance with ACI-440.2R.02 [34] yield conservative results and both need further refinement for achieving improved results..

References

[1] IS: 456-2000, Code of practice for plain and reinforced concrete, Bureau of Indian Standards, New Delhi.

[2] H.Saadatmanesh, Ehsani, M. R.. Ehsani, and M. W. Li, “Strength and ductility of concrete columns externally reinforced with fibre composite straps”, ACI Structural Journal, vol 91(4), pp. 434-447 , 1994.

[3] M. Demers, and K. W. Neale, “Confinement of reinforced concrete columns with fibre reinforced composite sheets- an experimental study”,Can. Journal Civil Engineering, Vol. 26, pp.226-241,1999.

[4] T. C. Rousakis, A. I. Karabinis, and P. D. Kiosis, “FRP confined concrete members:Axial compression experiments and plasticity modeling”, Engineering Structure, Vol.29, No.7, PP.1343-1353,2007.

[5] A.Ilki, O. Peker, E. K. Karamuk, C. Demir, and N. Kumbasar, “FRP Retrofit of low and medium strength circular and rectangular reinforced concrete columns”, Journal of Material Civil Engineering, Vol. 20, No.2, pp.169-188, 2008.

[6] H. L. Wu, Y. F. Wang, L. Yu, and X. R. Li, “Experimental and computational studies on high strength concrete circular columns confined by aramid fibre reinforced polymer sheets”, Journal Composite Construction, Vol. 13, No. 2, pp. 12-134, 2009.

[7] C.Cui, and S. A. Sheikh, “Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers.” Journal of Composites for Construction, Vol. 14, No. 5, 2010.

[8] S. Matthys, H. Toutanji, K. Audenaert and L. Taerwe, “Axia load behavior of large-scale columns confined with fibre reinforced polymer composites”, ACI Structural Journal, Vol. 102, No.2, pp.258-267, 2005.

[9] A.De Luca, F. Matta, and A. Nanni “Behaviour of full scale GFRP reinforced concrete columns under pure axial load” , ACI Structural Journal, Vol. 107, No.5, pp.589-596, 2010.

[10] A.De Luca, F. Nardone, F. Matta, A. Nanni, G. P. Lignola, and A. Prota, “Structural Evaluation of Full-Scale FRP-Confined Reinforced Concrete

Columns" , Journal of Composites Construction, Vol. 15, No. 1, pp.112-123, 2011.

[11] A.Mirmiran, and M. Shahawy, "Behavior of concrete columns confined by fiber composite." Journal of Structural Engineering, Vol 123, No. 5, pp.583–590, 1997.

[12] S. Pessiki, K.A. Harries, J. T. Kestner, R. Sause, and J. M. Racles, "Axial behavior of reinforced concrete columns confined with FRP jackets", Journal Composite Construction, Vol. 5, No. 4, pp. 237-245, 2001.

[13] K. H. Tan, "Strength enhancement of rectangular reinforced concrete columns using fibre reinforced polymer", Journal of Composites for Construction, Vol. 6, No. 3, pp. 175-183, 2001.

[14] O. Chaallal, and M. Shahawy, and M. Hassan, "Performance of axilly loaded short rectangular columns strengthened with carbon FRP wrapping", Journal of Composites for Construction, Vol. 7, No. 3, pp. 200-208, 2003.

[15] R. Kumutha, R. Vaidyanathan, and M. S. Palanichamy, "Behaviour of reinforced concrete rectangular columns strengthened using GFRP." Cement Concrete Composites, Vol 29, No. 8, pp.609–615, 2007.

[16] L. M. Wang, Y. F. Wu, "Effect of corner radius on the performance of CFRP-confined square concrete columns:test", Engineering Structure, Vol.30, No.2, PP.493-505, 2008.

[17] T. Turgay, Z. Polat, H.O. Koksal, B. Doran, and C. Karakoc, "Compressive bahaviour of large scale square reinforced concrete columns confined with carbon fibre reinforced polymer wraps", Material Des., Vol. 31, No. 1, pp.357-364, 2010.

[18] Z. Wang, D. Wang, S. T. Smith, and D. Lu, "CFRP-Confined Square RC Columns. I: Experimental Investigation", Journal of Composites for Construction, Vol. 16, No. 2, 2012.

[19] M.R. Spoelstra and G. Monti, "FRP confined concrete model", Journal of Composites for Construction, Vol. 3, No. 3, pp. 143-150, 1999.

[20] A.Z. Fam and S.H. Rizkalla, "Confinement model for axially loaded confined by circular fibre reinforced polymer tubes", ACI Structural Journal, Vol. 98, No. 4, pp. 451-461, 2001.

[21] K.A. Harries and G. Kharel, "Behaviour and modeling of concrete subject to variable confining pressure", ACI Materials Journal, Vol. 99, No. 2, pp. 180-189, 2002.

[22] L. Lam and J. G. Teng, "Design-oriented stress-strain model for FRP-confined concrete", Construction Building Material, Vol. 17, No.6-7, pp.471-489, 2003.

[23] J. G. Teng and L. Lam, "Behaviour and modeling of fibre reinforced polymer-confined concrete", Journal of Structural Engineering, Vol. 130, No.11, pp.1713-1723, 2004.

[24] J.G. Teng, T. Jiang, L. Lam and Y.Z. Luo, "Refinement of a design-oriented stress-strain model for FRP confined concrete", Journal of Composites for Construction, Vol. 13, No. 4, pp. 269-278, 2009.

[25] C. Cui and S. A. Sheikh, "Analytical model for circular normal and high strength concrete columns confined with FRP", Journal of Composites for Construction, Vol. 14, No. 5, pp. 562-572, 2010.

[26] A. Mirmiran, M. Shahawy, M. Samaan, H.E. Echary, J. C. Mastrapa and O. Pico, "Effect of column parameters on FRP confined concrete", Journal of Composites for Construction, Vol. 2, No. 4, pp. 175-185, 1998.

[27] Y.C. Wang and J.I. Restrepo, "Investigation of concentrically loaded reinforced concrete columns confined with glass fibre reinforced polymer jackets", ACI Structural Journal, Vol. 98, No. 3, pp.377-385, 2001.

[28] G. Campione, and N. Miraglia, "Strength and strain capacities of concrete compression members reinforced with FRP", Cement Concerte Composites, Vol. 25, No. 1, pp. 31-41, 2003.

[29] L. Lam and J. G. Teng, "Design-oriented stress-strain model for FRP-confined concrete in rectangular columns", Journal of Reinforced Plastic Composites, Vol. 22, No.13, pp.1149-1186, 2003.

[30] M. Maalej, S. Tanwongsval, and P. Paramasivam, "Modelling of rectangular columns strengthened with FRP", Cement Concerte Composites, Vol. 25, pp.263-276, 2003.

[31] M. H. Haraji, E, Hantouche, and K. Soudki, "Stress-strain model for fibre reinforced polymer jacketed concrete columns", ACI Structural Journal, Vol. 103, No. 5, pp.672-680, 2006.

[32] A.De Luca and A. Nanni, "Single parameter methodology for prediction of the stress-strain behavior of FRP confined RC square columns", Journal of Composites for Construction, Vol. 15, No. 3, pp. 384-392, 2011.

[33] C.Pellegrino, and C. Modena, "Analytical Model for FRP Confinement of Concrete Columns with and without Internal Steel Reinforcement", Journal of Composites for Construction, Vol. 14, No. 6, pp. 693-705, 2010.

[34] American Concrete Institute, "Guide for the design and construction of externally bonded FRP systems for strengthening of concrete structures", ACI 440.2R-02, Farmington Hill, Michigan, 2002.

[35] The Concrete Society (UK), "Design guidance for strengthening concrete structures using fibre composite materials", Technical Report No. 55, 2000.

[36] FIB Bulletin 14, "Externally bonded FRP reinforcement for RC structures", Technical Report, International Federation of Structural Concrete, Lausanne, 2001.

[37] ISIS Canada, "Design Manuals Parts 1-4, Intelligent sensing of innovating structures University of Manitoba, Winnipeg, 2001.

[38] Japan Building Disaster Prevention Association (JBDPA), "Seismic retrofitting design and construction guidelines for existing reinforced concrete (RC) buildings with FRP materials" (in Japanese), Japan, 1999.

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