

A REVIEW ON STRENGTHENING OF REINFORCED CONCRETE ARCHES

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Abstract

Durability and serviceability are one of the primary concerns of reinforced cement concrete (RCC) structures. The RCC structures require periodic monitoring and strengthening with time to enhance the structural performance degraded by varieties of reasons. Arches are one of the extensively used structural elements and can be found in many structures which face the challenges of inadequacy to carry the new loading condition requirements. Furthermore, they suffer from degradation of structure, corrosion of reinforcement steel bars, bad conditions of weather and etc. Therefore, this paper focuses and reviews the materials, methods and processes for strengthening of reinforced concrete arches. The review includes the historical development of repair and strengthening techniques including the state of art material usage. A comparative study is carried out on the success ratio of different processes employed in the strengthening and repair of damaged arch. It is observed that the modern materials and techniques have raised the success ratio of strengthening of the RCC arches. The paper also investigates the current gap of the knowledge and limitations of the area of study and prospects on the future scope of experimental studies.

1. Introduction

Recently, due to insufficiencies of structures such as material deterioration or aging, poor maintenance, earthquakes and etc. and as built structures in past are not constructed as per new engineering codes of design which make them structurally unsafe and replacement of such structures require a huge amount and in the same time, it destroys their antiquity if they are of ancient time, have made number of researches to invent efficient, adequate and economical techniques for repairing and strengthening. Further, on account of aging process, insufficiency in maintenance, as well as the upshot resulting from inconvenient environmental conditions (e.g., local cracking of the concrete matrix and corrosion of reinforcement), the built bridges don't have an adequate safety limits against seismic failure.[1] In many structures nowadays reinforced concrete arches can be found, but historically as the supremacy of its shape that allows spanning over long distances, they may be used in construction of bridges. In many cases, the arches are designed with spandrel columns to behave in compression under symmetric vertical forces. [2] Because of improved traffic loads and modifications in the design codes, only few of these bridges encounter the available standard specifications for traffic loadings. Nevertheless, most of them are damaged because of some non-symmetric actions which induce considerable flexure in the form of cracks. [[3], [4], [5]] Arch bridges are not only the culture and heritage symbols but also are the ancient structural memorials which need to be protected. Such bridges have been using for servicing on road, railway and water networks. The arches basically work in compression which make probable by the horizontal reactions at the abutments to create a normal thrust over the arch. Most of the reinforced and pre-stressed concrete bridges which are constructed in the past are not entirely satisfactory according to their performance which need rehabilitation and strengthening. [2] Buckling and geometrical nonlinearities became critical aspects of the structural behavior. using traditional construction techniques and materials for reinforcing and retrofitting of available concrete structures in order to increase ductility, to resist higher design loads, to correct design or construction insufficiencies, and to correct capacity loss due to distress, have been performed conventionally. Some of the traditional techniques which have been performed conventionally for strengthening of structures are concrete or steel jackets, externally bonded steel plates, and external post-tensioning. In the construction industry, the use of FRP's applies primarily to the restoration of distressed structures and to improve statically and seismically behavior of the structures. [6] But for strengthening of RC arches as of its curved geometry, its load resistance mechanism (combined membrane and flexural actions), cracking pattern, and failure mechanisms, mostly externally bonded strengthening with FRP systems are used. Repairing and reinforcing of reinforced concrete or concrete structures by means of fiber reinforced polymer materials are a great revolutionary in the arena of structural engineering. Fiber reinforced polymer (FRP) is another method for reinforcing of structures rather than traditional methods. FRP composite materials are used alternatively as externally bonded reinforcement in FRP strengthening systems. Thus, mainly, the FRP strips play role in such reinforced RC arches to minimize the effects of geometric imperfections and to restrain/postpone extreme cracking and failure as a product of non-symmetric loading. [2] Its lightweight, easy setting up, and non-corrosiveness are the benefits of FRP methods over the traditional reinforcing methods. It is used for reinforcing of either new and already built structures. There are different kinds of FRP materials like Carbon, Glass, Aramid and etc. To wound the structural member, these sheets are used on external surface of the member and basis on the strength required, the

number of layers are selected. [6] Many researches have been done for strengthening of arches but there are few reported test results for reinforced RC arches. [2] This paper focuses on the materials, methods and processes for strengthening of reinforced concrete arches. A comparative study is carried out on the success ratio of different processes employed for the strengthening and repair of damaged arches.

Background Information and Historical Development of Strengthening Techniques

As most of the RC arches are strengthened with externally bond FRP techniques therefore the development and historical information of the FRP will be discussed here. The ideology and theory of retrofitting and reinforcing of structures by means of fiber reinforced polymer strengthening is not new. The primary improvements of FRP methods for retrofitting and reinforcing of structures emerged in the mid of 1980s either in Japan and Europe. For repairing, retrofitting and reinforcing of available structures, FRP reinforcing methods have been utilized across the globe. Externally bonded FRP methods were established as a substitute to other external reinforcing methods like jacketing of steel or concrete column and etc. The number of strengthened projects has been increased considerably. Elements or members of structures like slabs, beams, columns, connection/joints, walls, chimneys, smokestacks, domes, vaults, silos, tunnels and pipes have been reinforced using this technique. In spite of using FRP reinforcement methods in concrete, they also have been used for reinforcement of steel, timber, masonry and cast-iron structures. [9]

Europe has developed FRP techniques as substitutes to steel plate bonding for multiplying the flexural capacity of concrete structure elements.[[9], [10]]. This technique has been used to reinforce and retrofit many structures such as bridges and buildings across the world. Researchers have looked to find a substitute way to steel because steel requires heavy equipment and is difficult to install and as steel plates can corrode, which causes destruction of the bond between steel and concrete thus they have found FRP materials. In 1978 Germany researched experimentally using of FRP materials for reinforcing and retrofitting of concrete structures. [[9], [11][12]]. In Switzerland research showed the first application of externally bond FRP techniques to reinforced concrete bridge for flexural reinforcing. [[9][13]] In 1980s Japan firstly applied FRP techniques to strengthen concrete columns for giving extra confinement [[9][14]]. After 1995 Hyogoken-Nanbu earthquake in Japan, there was an abrupt growth in the usage of FRPs as strengthening technique. [[9], [15]]. In the United States researchers have had a continues interest in reinforcement of concrete structures with fiber reinforcement polymer since 1930s. Improvement and investigation in the installing of these materials as retrofitting medium for reinforcing of structures started in the 1980s through the inventions of the Federal Highway Administration (FHWA) and the National Science Foundation (NSF). The research activities directed to the establishment of many field projects that encompassed a wide diversity of environmental conditions. [[9], [16] -[22]

United States, Canada and Europe are developing standards and codes for FRP techniques. For application of FRP materials in concrete structures, the Railway Technical Research Institute (RTRI), the Japan Concrete Institute (JCI) and the Japan Society of Civil Engineers (JSCE) researched and published different papers and documents. Task Group 9.3 of the International Federation for Structural Concrete (FIB) in Europe issued a design guideline for externally bonded FRP techniques for strengthened concrete structures.[23] The Canadian Standards Association (CSA) and ISIS also developed guidelines of FRP techniques for reinforcing of structures. Canadian Highway Bridge Design code section 16, "Fiber Reinforced Structures," was finalized in 2006 and was approved by (CAN/CSA-S6-06) and CSA.[24]

1. Research Findings

Strengthening is the process which increases the initial designed performance of the structures and add capacity to structural member. When the loads on the structures increase, this process is needed. [25] In civil engineering, Fiber Reinforced Polymers (FRPs) have been broadly applied for improving the capacity and to retrofit distressed structures. This technique has been utilized to arch structures too. In unreinforced arches only strengthening continuously can avoid typical local failure mechanisms. The most efficient possibility to improve capacity of arches is reinforcement at the intrados. High deformation capability prior to failure achieves in reinforcing of extrados and endows arches with remarkable ductility behavior.[36] The FRP strengthening methods can efficiently increase the load carrying capacity of reinforced concrete arches. Peak load of the reinforced arches with FRP fails with an improvement of 21% and 40% and a remarkable improve of the deformability at failure. The weakest section where has less or no bonded FRP strips is affected by critical cracks.[2] Blast reactions of CFRP reinforced arches was discussed experimentally by Chen et al. and Xie et al. [26] At first, they strengthened the arch by means of externally bonded CFRP sheet, but in dynamic de-bonding, the reinforcing influence was diminished. Afterward, Chen et al, for restricting the dynamic de-bonding, used anchoring/bonding method. Nam et al. [30] studied numerically reaction of concrete arches which are reinforced by FRP. A group of researchers from University of Chongqing Jiaotong [[28][29]] investigated efficiency of bridge arches reinforced via CFRPs and GFRPs and proposed 3 reinforcing schemes: (i) O-Style; (ii) U-Style and (iii) I-Style.

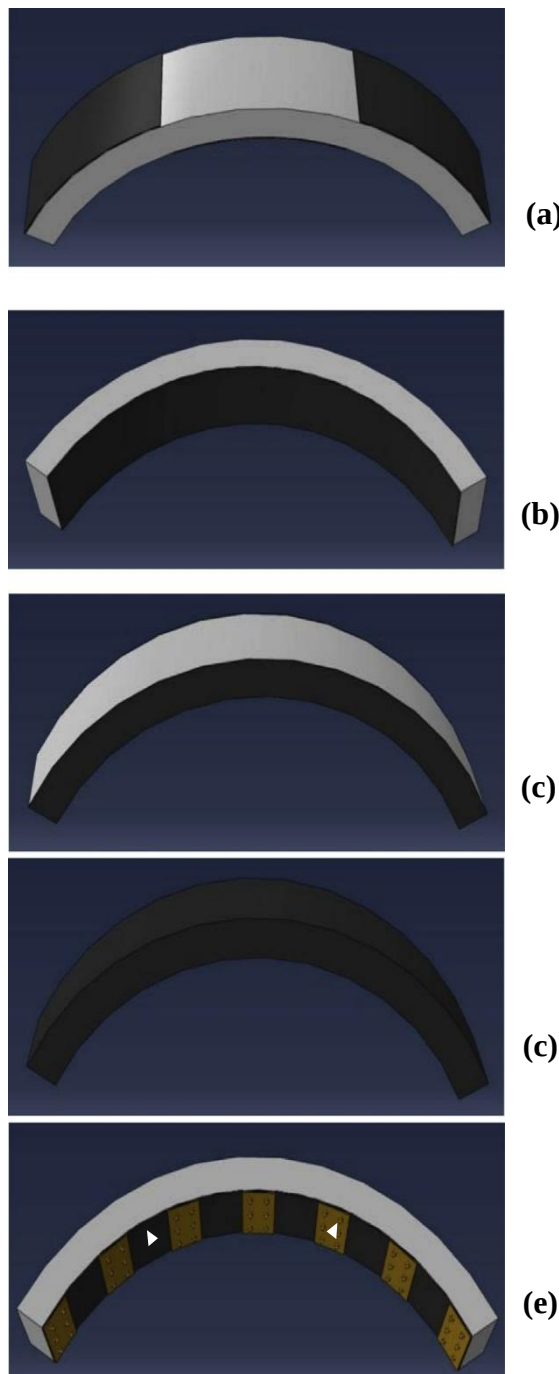


Fig. 1. Strengthening schemes: (A) Bonding method, consist of i) I-style bonding ii) intrados bonding (B) Wrapping method, consist of iii) U-style bonding iv) O-style bonding and (C) v) anchoring or Intrados bonding method. [8]

Impact of CFRPs for reinforcement of masonry arches was focused more by most researchers. [31] But Hamed et al. [2] researched on strengthening of R.C. arches using CFRPs as externally bonded and he found the ultimate force of reinforced arch with a peak improvement of 40%. Dagher et al.[27] suggested for bridges structures, concrete filled tubular FRP arches which it makes a unique usage of CFRP for reinforcement of arch structures. For strengthening of concrete arches, 3 methods are used: (a) wrapping method; (b) bonding method; and (c) anchoring/bonding method, as demonstrated in Fig. 1. For bonding method, the concrete arch is reinforced using CFRP strips on the inside and outside of the arch as I-style for arch bridge structures. In bridge arches, for restricting de-bonding, the FRP strips can be wrapped around the cross section. To improve the shear capacity and provide high de-bonding resistance, CFRP strips are employed on the web in inroads CFRP reinforcing method. Using such schemes of reinforcement can substitute reinforced concrete member to concrete

member since CFRP strips are used instead of steel re-bars. The wrapped concrete by means of CFRP strips behaves like 3-dimensionally constrained and caused ductile. Underground arches cannot be wrapped as only one surface is accessible therefore Intrados bonding and anchoring/bonding methods are applicable. FRP strips are used only on the interior surface of the arch if it is buried underground. For intrados bonding method, the basic failure is de-bonding, particularly at the vault and for resisting of the de-bonding, mechanical fasteners are used periodically distributed on the internal surface of the arch. Effect of strengthening is related to strengthening schemes. As demonstrated in Table 1. O-style is the most effective method which significantly reaches the ultimate peak load of reinforced concrete arch. In this research the span of arch 2.4 m, rise of arch as 0.6 m and 0.5 for its rise to span ration are considered, the width of arch is taken 0.15 m with thickness of 0.1 m as presented in Table 1. The steel reinforcement ratio for CR2, CR3 and CR4 arches is 0.337% and CFRP ratio is 0.167% of both extrados and intrados, respectively.[28][29][8] Before the failure of the material, CFRP de-bonding was not considered. The increase was about 30.7%. But in U-style reinforcing scheme the development was 46.7%. While in I-style reinforcing scheme, the development was only 7.8%. The impacts of reinforcing are considerable in concrete arches. In case of concrete arches as demonstrated in Table 1. the arch C4 has a peak load of five-times higher than arch C1 and even higher than RC arches if strengthened as O-style. The two other arches C2 and C3 are reinforced by other two schemes which have 3 times higher peak loads. [29]

Hamed et al. also applied I-style strengthening in RC arches. The arch's rise is 0.6m, its span is 4.27m and the rise-to-span ratio is considered 0.14. The thickness is considered as 0.08m and its width is 0.3m. 0.353% is the steel ratio and 0.35% is considered as CFRP strengthening ratio in both internal and external surfaces of the arch respectively. [2] For preventing local shear failure, the loaded locations of the A3 arch was wrapped. There was a highest improvement of 38.9% in ultimate load of A3 arch. The improvement is about 20.6% for arch A2 and the de-bonding was considered. With higher CFRP reinforcement ratio and lesser rise-to-span ratio, the reinforcing effectiveness of I-style is improved from 7.8% to 20%.

Strengthening result of GFRP strengthened arches (G2, G3 and G4) are so smaller[8][35] as presented in Table 1.

Table 1

Characteristic of the strengthened arches [6–9].

Arch Name	Geometry of Arch	Material of Arch	Type of FRP	FRP Ratio	Scheme of Strengthening	Ultimate Load (Kn)	Increment (%)	References
CR1	Span: 2.4 m Rise: 0.6 m	RC arch,	Controlling arch	-	None	130.2		Wang [6]
CR2			CFRP,	0.167	I-style	140.4	7.8	
CR3			CFRP	0.167	U-style	191.0	46.7	
CR4			CFRP	0.334	O-style	170.2	30.7	
C1	Span: 2.4 m Rise: 0.6 m	Concrete	Controlling arch	-	None	32.8	-	Sun [7]
C2			CFRP	0.167	I-style	142.3	333.8	
C3			CFRP	0.167	U-style	127.8	289.6	
C4			CFRP	0.334	O-style	199.2	507.3	
G1	Span: 2.4 m Rise: 0.6 m	Concrete	Controlling arch	-	None	35.0	-	Tu [8]
G1			GFRP, –	-	I-style	60.2	72	
G3			GFRP, –	-	U-style	78.1	123.1	
G4			GFRP, –	-	O-style	85.7	144.9	
A1	Span: 4.27 m Rise: 0.6 m	RC arch,	Controlling arch	-	None	30.6	-	Hamed et al. [9]
A2			CFRP, 0.5%	0.5%	Bonding	36.9	20.6	
A3			CFRP, 0.5%	0.5%	Bonding/wrapping	42.5	38.9	

Xu Zhang [8] revealed the impact of rise-to-span ratio of semi-circular arches strengthened by CFRP. Totally 5 arches were tested. One as controlling arch, 2 of them were reinforced with intrados bonding method and 2 with intrados/bonding method as demonstrated in table 3. The load was applied on the controlling arch at the vault and initially cracks observed on the internal surface at the vault. In arch R2 and R3 de-bonding was observed on the external surface at the vault when the deflection was 2.4mm and 2.4mm respectively, as demonstrated in Table 3. De-bonding of the CFRP sheets were not obtained at the vault due to wrapping and transferred to the internal surface of the arch between the wraps while the deflection was 3.3mm and 2.8mm respectively.

Table 3

Specification of the strengthened arches by Xu Zhang [8]

Arc h	Strengthening method	CFRP style	CFRP ratio	Ultimate load (kN)	Increase in ultimate load (%)	Increase in stiffness (%)
R1	Control arch			106.1		
R2	Intrados bonding	Sheet	0.11%	103.4	2.54	76.1
R3	Intrados bonding	Strip	0.93%	106.3	0.19	72.7
R4	Intrados bonding/wrapping	Sheet	0.11%	120.9	13.95	115.9
R5	Intrados bonding/wrapping	Strip	0.93%	114.4	7.82	118.2

As demonstrated in Fig. 2, for rise-to-span ratio of 0.14 the increment in the capacity of the arch strengthened by wrapping method is 0.398, for rise-to span of 0.25, the increment in the capacity is 0.307 and for the rise-to-span ratio of 0.5, the increment was observed only 0.14. But in wrapped semi-circular arch, the ductility and stiffness are achieved. [8]

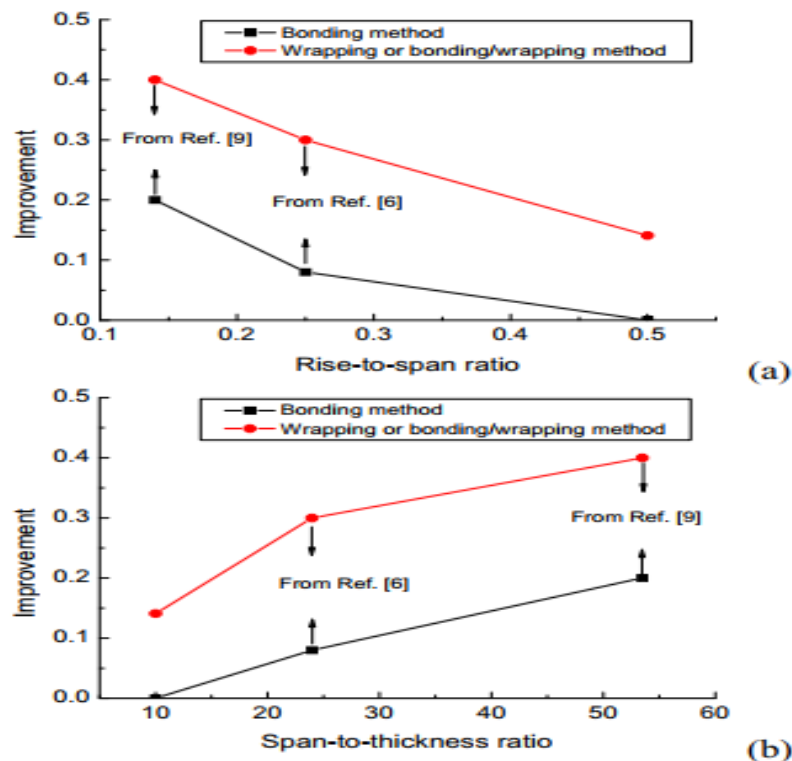


Fig.2: Load carrying capacity improvement related to i) rise-to-span ratio and ii) span-to-thickness ratio

FRP reinforcement techniques for concrete arches are effective to increase their strength especially CFRP. The ultimate load of the reinforced arches according to experiments is four times more than the un-reinforced arch. The increment is remarkable that the strengthened concrete arch even has as good strength as the reinforced RC arch.

2. Conclusions

1. This research shows that advantage of FRP for improving load carrying capacity of arches depends on the material of arch, the ratio of rise-to-span and the method of reinforcing.
2. The FRP strengthening methods can efficiently improve the load carrying capacity of reinforced concrete arches.
3. The position of the critical crack transfers to the locations where there is no or less bonded FRP strips.
4. Normal de-bonding happens if the tensile crack of concrete develops on the internal surface at the vault and de-bonding can cause decrease in reinforcing effect.
5. Several design issues and material exist particularly to FRP which need modifications to the design codes.
6. The number of experimental studies or applications using FRP- composites for reinforcing of RC arches is less.
7. This research shows that some points need more illuminated. These comprise consideration of various imperfection scenarios, the cracking effects and material nonlinearity, and the features that govern the stable de-bonding.
8. In the future one of the key areas in development of bridge will be the rehabilitation, strengthening and retrofitting of deteriorated and distressed bridges.

References

- [1]. Zanardo, G., Pellegrino, C., Bobisut, C., and Modena, C. "Performance evaluation of short span reinforced concrete arch bridges." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2004)9:5(424), 424–434.
- [2]. Hamed E, Chang ZT, Rabinovitch O. Strengthening of reinforced concrete arches with externally bonded composite materials: testing and analysis. *J Compos Constr* 10.1061/(ASCE)CC.1943-5614.0000495, 2014, Vol. 19, Issue 1, 1-15, (February 2015).
- [3]. Zanardo, G., Pellegrino, C., Bobisut, C., and Modena, C. (2004). "Performance evaluation of short span reinforced concrete arch bridges." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2004)9:5(424), 424–434.
- [4]. Avossa, A. M., Famigliuolo, P., and Malangone, P. (2008). "Structural safety evaluation of a R.C. arch bridge." *Life-cycle Civil Engineering-Proc.*, 1st Int. Symp. on Life-Cycle Civil Engineering, CRC Press, Taylor & Francis Group, London, ISBN 978-0-415-46857-2, 2008, 697–702.
- [5]. Muktar Nuhu Danraka, H. Mahir Mahmod, Ojo-kupoluyi Job Oluwatosin, (2017). "Strengthening of Reinforced Concrete Beams using FRP Technique: A Review", *International Journal of Engineering Science and Computing*, 13199–13213.
- [6]. Structural strengthening manual MAPEI SpA, E-mail: mapei@mapei.it
- [7]. Rajat Sachdeva, Harish Singh, "A Review of Application of GFRP in Shear and Flexure to Strengthen the Reinforced Concrete Beam", *IJERT*, 2017, 1–5.
- [8]. Xu Zhang, Peng Wang, Meirong Jiang, Hualin Fan, Jiannan Zhou, Wanxin Li, Lu Dong, Hailong Chen, Fengnian Jin "CFRP strengthening reinforced concrete arches: Strengthening methods and experimental studies," *Composite Structures*, Volume 131, 1 November 2015, Pages 852-867
- [9]. ACI 440.2R-08. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. Farmington Hills, MI: ACI; 2008.
- [10]. Fleming, C. J., and King, G. E. M., 1967, "The Develop- ment of Structural Adhesives for Three Original Uses in South Africa," *RILEM International Symposium, Synthetic Resins in Building Construction*, Paris, pp. 75-92.
- [11]. Wolf, R., and Miessler, H. J., 1989, "HLV-Spannglieder in der Praxis," *Erfahrungen Mit Glasfaserverbundstaben*, Beton, 2, pp. 47-51.
- [12]. Dolan, C. W.; Rizkalla, S. H.; and Nanni, A., eds, 1999, *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, SP-188, American Concrete Institute, Farmington Hills, MI.
- [13]. . Rostasy, F. S., 1987, "Bonding of Steel and GFRP Plates in the Area of Coupling Joints. Talbrucke Kattenbusch," *Research Report No. 3126/1429*, Federal Institute for Materials Testing, Braunschweig, Germany. (in German).
- [14]. Fardis, M. N., and Khalili, H., 1981, "Concrete Encased in Fiberglass Reinforced Plastic," *ACI JOURNAL*, Proceedings V. 78, No. 6, Nov.-Dec., pp. 440-446.
- [15]. . Kumahara, S.; Masuda, Y.; and Tanano, Y., 1993, "Tensile Strength of Continuous Fiber Bar Under High Temperature," *International Symposium on Fiber-Reinforced Plastic Reinforcement for Concrete Structures*, SP-138, A. Nanni and C. W. Dolan, eds., American Concrete Institute, Farmington Hills, MI, pp. 731-742.
- [16]. Neale, K. W., 2000, "FRPs for Structural Rehabilitation: A Survey of Recent Progress," *Progress in Structural Engineering and Materials*, V. 2, No. 2, pp. 133-138.
- [17]. Dolan, C. W.; Rizkalla, S. H.; and Nanni, A., eds, 1999, *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, SP-188, American Concrete Institute, Farmington Hills, MI.

- [18]. Sheheta, E.; Morphy, R.; and Rizkalla, S., 1999, Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, SP-188, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., American Concrete Institute, Farmington Hills, MI, pp. 157-167.
- [19]. Malek, A.; Saadatmanesh, H.; and Ehsani, M., 1998, "Prediction of Failure Load of R/C Beams Strengthened with FRP Plate Due to Stress Concentrations at the Plate End," ACI Structural Journal, V. 95, No. 1, Jan.-Feb., pp. 142-152.
- [20]. Benmokrane, B., and Rahman, H., eds., 1998, Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, University of Sherbrooke, Canada.
- [21]. Neale, K. W., and Labossière, P., 1997, "State-of-the-Art Report on Retrofitting and Strengthening by Continuous Fibre in Canada," Non-Metallic (FRP) Reinforcement for Concrete Structures, V. 1, Japan Concrete Institute, Tokyo, Japan, pp. 25-39.
- [22]. Hassan, T., and Rizkalla, S., 2002, "Flexural Strengthening of Pre-Stressed Bridge Slabs with FRP Systems," PCI Journal, V. 47, No. 1, pp. 76-93.
- [23]. Shield, C. K.; Busel, J. P.; Walkup S. L.; and Gremel, D. D., 2005, Proceedings of the Seventh International Symposium on Fiber Reinforced Polymer for Reinforced Concrete Structures (FRPRCS-7), SP-230, ACI, Farmington Hills, MI, 1708 pp.
- [24]. Atsuhiko Machida and Kyuichi Maruyama, "Design code development for fibre-reinforced polymer structures and repairs" Progress in Structural Engineering and Materials banner, Volume4, Issue2, April/June 2002, Pages 149-160.
- [25]. Mohamed Abd Elmoneam Zaky, Repair and Strengthening of Reinforced Concrete Structures, Ain Shams University, June 2013.
- [26]. Xie W, Jiang MR, Chen HL. Experimental behaviors of CFRP sheet reinforced buried arch structure subjected to subsurface localized explosion. Compos Struct 2014;116:562–70.
- [27]. Dagher HJ, Bannon DJ, Davids WG, et al. Bending behavior of concrete-filled tubular FRP arches for bridge structures. Constr Build Mater 2012; 37:432–9.
- [28]. Wang X. Experimental study on strengthening concrete arch with carbon fiber reinforced polymer (CFRP) (Dissertation). Chongqing: Chongqing Jiaotong University, 2013.
- [29]. Sun GJ. The study on performance of concrete composite arch reinforced with CFRP (Dissertation). Chongqing: Chongqing Jiaotong University, 2013.
- [30]. Nam JW, Kim HJ, Yi NH, et al. Blast analysis of concrete arch structure for FRP retrofitting design. Comput Concr 2009;6:305–18.
- [31]. Rovero L, Focacci F, Stipo G. Structural behavior of arch models strengthened using fiber-reinforced polymer strips of different lengths. J Compos Constr 2013;17:249–58.
- [32]. Caporale A, Feo L, Hui D, et al. Debonding of FRP in multi-span masonry arch structures via limit analysis. Compos Struct 2014; 108:856–65.
- [33]. D'Ambrisi A, Feo L, Focacci F. Masonry arches strengthened with composite unbonded tendons. Compos Struct 2013; 107:323–9.
- [34]. Chen JF. Load-bearing capacity of masonry arch bridges strengthened with fibre reinforced polymer composites. Adv Struct Eng 2002; 5:37–44.
- [35]. Tu ZZ. The study on performance of concrete arch reinforced with GFRP (Dissertation). Chongqing: Chongqing Jiaotong University, 2011.
- [36]. Daniel V. Oliveira, Ismael Basilio; and Paulo B. Lourenço, "Experimental Behavior of FRP Strengthened Masonry Arches," Journal of Composites for Construction, Volume 14 Issue 3 - June 2010, pages 312 – 322.