FLEXURAL STRENGTHENING OF TIMBER FLOOR GIRDERS

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Abstract

Flexural strengthening of timber floor girders in cultural heritage structures through externally bonded Fiber Reinforced Polymers (FRP) in the form of laminates, rods and bundled fibers was experimentally investigated and reported herein. The main variables were the cross-sectional shape of FRP laminate (round or plate), strengthening configurations (bonding directly to the tension face or embedded into the grooves carved on the tension face of the girder) and number of FRP laminates, hence the total x-sectional area of the FRP. The strengthened girders exhibited an increase in the load carrying capacity up to 90%, and a maximum deflection up to 90%, with respect to the control specimen without any strengthening.

Introduction

Wood as structural material has been widely used in the cultural heritage buildings, mostly as roof and slab girders or as structural wall verticals and diagonals against seismic excitations. Although, it has superior mechanical properties, timber may suffer flexural failures due either to excessive loads or aging losses. Many timber floor covers may have high cultural heritage value, and during a repair or restoration work the girders of such floors may need repairing instead of a complete renewal.

In the recent decade, fiber reinforced polymers gained popularity and became a commonly used material for strengthening purposes in civil engineering structures. This was mainly due to their high tensile strength over self-weight ratio and superior durability properties. The pioneering investigations on FRP strengthening of timber beams for enhancing the flexural strength were performed by Plevris and Triantafillou (1992) and Triantafillou and Deskovic (1992). Extensive research was conducted on bending behavior of timber beams that were strengthened with various applications of different FRP materials (Johns and Lacroix 2000, Fiorelli and Dias 2002, Schober and Rautenstrauch 2005). Furthermore, the reinforcing effect of GFRP rebars that were embedded into the grooves located on tension side of the timber girders were studied by Gentile 2000, Svecova and Eden 2004, and Yusof and Saleh 2010.

The main objective of the study given here is to investigate the effect of different FRP laminate types and application details on the performance of existing timber structures. In addition, the effect of aging on the strengthening performance is also investigated by using old timbers from cultural heritage structures under restoration.

Materials

Timber

Two different sets of timber specimens were tested. The first set of specimens consist of a newly cut yellow pine girders, whereas the second set consist of old black pine timber girders that were gathered from Tavsancıl Çarsı Mosque that was in service for approximately 200 years (constructed in 1818 by Hacı Veliyiddin Ağa, a merchant from Istanbul)

Fiber Reinforced Polymers

Four types of carbon fiber reinforced polymers (CFRP) were used for the flexural strengthening of the timber beams. Two CFRP plates (Sika Carbodur XS1.524 and Sika Carbodur S512/80) with different dimensions (1.2x50 mm and 2.4x15 mm respectively) were bonded to the tension face of the timber beams. CFRP bars (Sika Carbodur BC12) were embedded to the tension face of the specimens. Last, carbon fiber strings (Sika-Wrap Anchor C) that are mainly used for anchoring purposes were bonded into the grooves as flexural reinforcement on the tension face. The metarial properties of CFRP laminates listed above are given below in Table 1.

Table 1 - Material properties of FRP (supplied by the manufacturer)

FRP Material	Ultimate Strain (%)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Thickness (mm)	Width or diameter (mm)
Carbodur BC 12	1.3	2200	165000	-----	12
Wrap Anchor C	0.74	1590	215000 (fibers only)	-----	10
Carbodur S512 /80	1.7	2800	165000	1.2	50
Carbodur XS1.524	1.3	2200	165000	2.4	15

Epoxy

A two component epoxy resin was used for the bonding of FRP materials to the timber girders. Recommended environmental temperature for the application of the epoxy is given as +8 to +35 ^{o}C, while the compressive and tensile strength of 7 days cured epoxy is reported as 85 MPa and 30 MPa respectively by the manufacturer.

Experimental Program and Test Specimens

The study was planned as a two stage experimental investigation. In the first stage, seven newly cut timber girders having approximate cross-sectional dimensions of 90 x 90 mm, with a span length of 1800 mm were tested under third point loading. Six of the girders were strengthened by using FRP composites, while the seventh one was used as control specimen (reference specimen) for comparison purposes. Four of the beams (XV1, XV2, WAC and BC) were cut to form grooves (having different dimensions depending on the type of FRP used for strengthening) through the tension face of the timber beams for the installation of FRP reinforcement (Figure 1). Specimens XV1 and XV2 having one and two grooves respectively were strengthened with Carbodur XS1.524 strips bonded into the grooves by using epoxy resin. Specimens WAC and BC were strengthened in similar manner by using Wrap Anchor C and Carbodur BC12 respectively. On the other hand, Carbodur XS1.524 and Carbodur 512/80 strips were externally bonded along the bottom face of specimens XH1 and SH1 respectively (Figıre 2).

In the second stage, four old timber girders (black pine) gathered from a historical mosque restoration project in Tavsancil, Kocaeli were tested. The girders having cross sectional dimensions of 150x100 mm and a span length of 1800 mm were cut into two matched sample (sister) specimens with cross sectional dimensions of 100x100 mm (main specimen to be strengthened) and 50x100 mm (control specimen without strengthening) in order to obtain a control specimen for each strengthened old black pine girder. Old timber girders were strengthened identical to the specimens SH1, XH1, XV1 and WAC under the light of the findings from yellow pine (newly cut) timber tests. Cross-sectional dimensions and strengthening methods of the test specimens are summarized in Table 2.

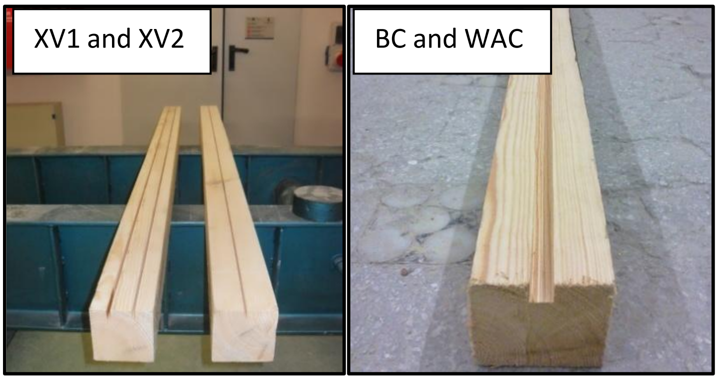

Figure 1 - Grooves prepared for FRP installation

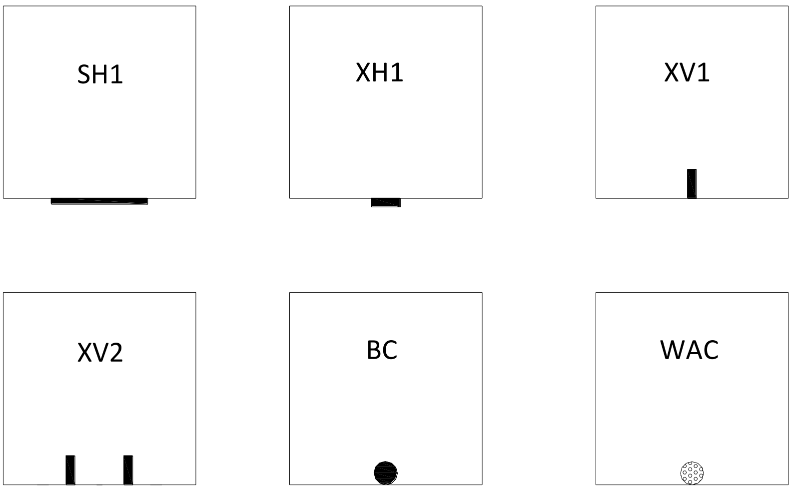

Figure 2 - FRP strengthening schemes of the test specimens

Table 2 - Cross-sectional dimensions and strengthening schemes

Series	No	Name	Strengthening	Width *(mm)*	Depth *(mm)*
Yellow Pine	1	R	None	90	92
	2	SH1	1 Ply of Carbodur S512/80 *(bonded to surface-horizontal)*	90	89
	3	XH1	1 Ply of Carbodur XS1.524 *(bonded to surface-horizontal)*	90	88
	4	XV1	1 Ply of Carbodur XS1.524 *(bonded into groove-vertical)*	88	89
	5	XV2	2 Ply of Carbodur XS1.524 *(bonded into groove-vertical)*	90	89
	6	WAC	Wrap Anchor C *(bonded into groove)*	91	92
	7	BC	Carbodur BC 12 (Rod) *(bonded into groove)*	91	90
Black Pine (old)	8	SH1-O-R	None *(control for SH1-O)*	55	98
	9	XH1-O-R	None *(control for XH1-O)*	48	94
	10	XV1-O-R	None *(control for XV1-O)*	52	96
	11	WAC-O-R	None *(control for AWC-O)*	52	96
	12	SH1-O	1 Plyof Carbodur S512/80 *(bonded to surface-horizontal)*	99	98
	13	XH1-O	1 Ply of Carbodur XS1.524 *(bonded to surface-horizontal)*	96	94
	14	XV1-O	1 Ply of Carbodur XS1.524 *(bonded into groove-vertical)*	95	96
	15	WAC-O	Wrap Anchor C *(bonded into groove)*	97	96

Test Setup and Instrumentation

All test specimens were tested under third point loading, keeping the shear span to depth ratio identical for all timber girders as shown in Figure 3. Simply supported boundary conditions were satisfied by using cylindrical bearings at the ends of the test specimens. The load was applied monotonically through an I-section spreader beam having clear span of 600 mm between the simply supported loading ends. The relative humidity of the environment was in the range of 45-55% during testing. Total of three linear variable deflection transducers (LVDTs) were placed to measure the vertical displacement in the mid-span and at the support locations.

Figure 3 - Test Setup

Test Results

The mid-span deflection vs. load curves of all test specimens were presented in Figures 4 and 5. The bending stiffness of the test specimens was computed by considering the proportional limit where the load-deflection curve deviates. Equation 1 is employed for calculation of the bending stiffness.

$$EI = \frac{P_p\, a\, (3L^2 - 4a^2)}{48\, \Delta_p} \qquad (1)$$

where P_p is the load at proportional limit, a is the distance between the support and the load application point (shear span), L is the span length, Δ_p is the deflection corresponding to the proportional limit load.

A normalization was applied to the measured loads and the calculated bending stiffness values (from equation 1) of black pine (old) reference specimens since the width of the reference specimens were almost equal to one half width of the strengthened specimens. The calculated EI values, hence the measured load values, were multiplied with a coefficient equal to b_s / b_r, where b_s is the width of the strengthened specimen while b_r is the width of the reference specimen. The test results are given in Table 3 and 4.

The test results revealed that the application of externally bonded CFRP, either surface bonded or groove bonded, yielded reasonable enhancements in the ultimate load carrying capacity, proportional limit hence the flexural stiffness of the timber floor girders. The approximate enhancement in the failure load of the yellow pine timbers was in the range of 40% through the surface bonding of Carbodur S512/80, while the enhancement in the flexural stiffness was 20%. Such findings indicate that not only the load carrying capacity but also the serviceability limits may be modified through CFRP applications for the newly cut yellow pine timbers. The companion enhancement values in the old black pine timbers were approximately 90%. Such an enhancement may well be attributed to the significant effectiveness of the CFRP strengthening on weak and aged timbers, which is a very promising finding.

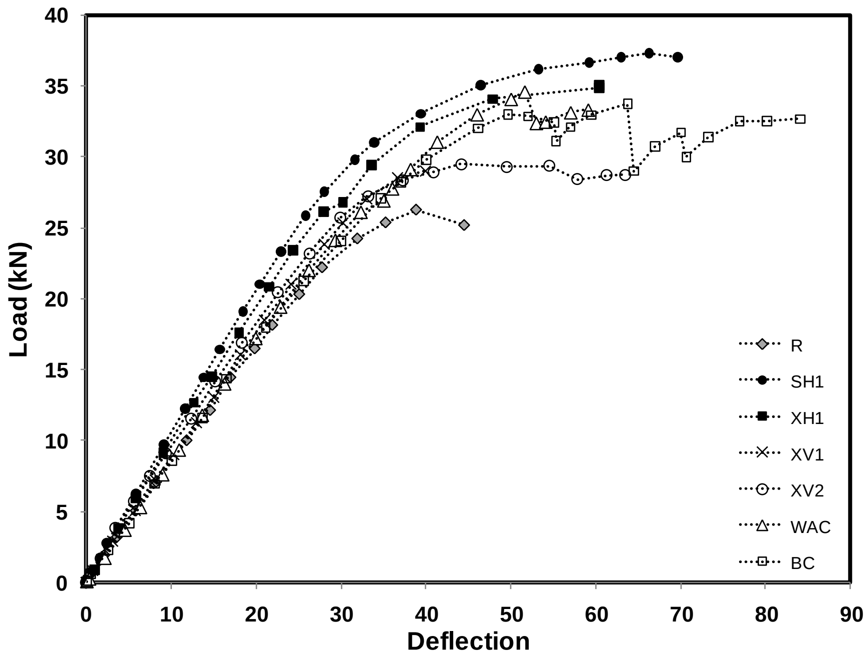

Figure 4 – Load-deflection response of Yellow Pine Specimens

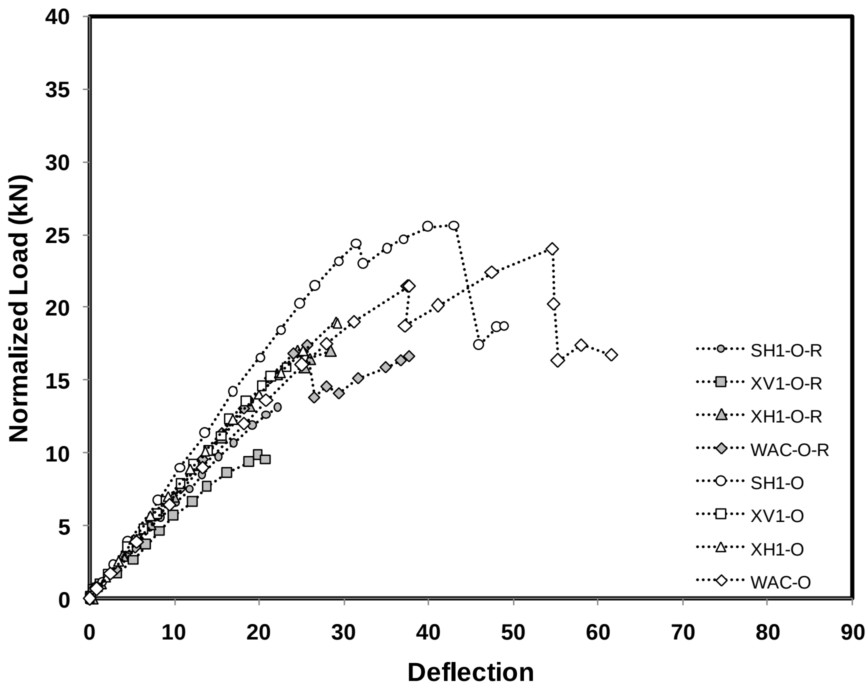

Figure 5 – Load-deflection response of Black Pine Specimens

Table 3 - Test Results of Yellow Pine Specimens (new)

Series	Name	A_{CFRP} (mm^2)	P_u (kN)	Δ_u (mm)	P_p (kN)	Δ_p (mm)	EI ($kN.m^2$)
Yellow Pine	R	---	26.48	43.26	21.10	26.18	83.43
	SH1	60	37.05	69.69	25.25	25.08	103.97
	XH1	36	34.88	60.42	23.50	24.47	99.44
	XV1	36	29.03	39.94	25.06	29.73	86.80
	XV2	72	28.75	63.47	24.12	27.51	90.76
	WAC	78.5	33.42	58.72	25.63	31.64	83.85
	BC	113	32.81	85.57	24.26	30.16	83.35

Table 4 - Test Results of Black Pine Specimens (old)

Series	Name	A_{CFRP} (mm^2)	P_u (kN)	Δ_u (mm)	P_p (kN)	Δ_p (mm)	EI ($kN.m^2$)
Black Pine (old)	SH1-O-R	---	13.14	22.23	11.20	17.89	64.80*
	XH1-O-R	---	17.02	28.47	16.48	23.84	71.50*
	XV1-O-R	---	9.87	26.11	8.39	15.84	54.84*
	WAC-O-R	---	17.76	25.69	17.38	25.69	69.97*
	SH1-O	60	25.80	41.15	22.02	27.52	82.82
	XH1-O	36	19.05	29.22	13.51	19.16	73.28
	XV1-O	36	15.94	23.21	15.94	23.21	71.09
	WAC-O	78.5	24.05	54.89	16.75	26.51	65.40

* Normalized values.

Failure modes

Typically observed failure modes for timber beams subjected to bending action can be classified as simple tension, cross grain tension and compression failures. The yellow pine control specimens were first underwent minor compressive crushing, followed by simple tension failure. On the other hand the black pine control specimens experienced pure simple tension failures. This difference may well be due to the material variety of different pine species. The failure of yellow or black pine specimens strengthened with surface bonded Carbodur XS1.524 was initiated with the debonding of the CFRP laminates from the tension face of the specimen (yellow pine underwent minor compressive crushing before debonding). This was mainly due to the small bonding surface area of the Carbodur XS1.524 with respect to its x-sectional area. On the other hand, the yellow pine specimen strengthened with Carbodur S512/80 reached its ultimate load capacity through the compression crushing, while the companion black pine specimen failed through debonding. The specimens strengthened with groove bonded Carbodur XS1.524, either yellow or black pine, failed primarily due to the slippage of CFRP within the grooves, followed by either simple tension or cross-grain tension failure. The specimens strengthened with Wrap Anchor C or Carbodur BC 12 underwent very similar failures.

cross grain tension failure

simple tension

Figure 6 – Types of tension failures in timber beams

Acknowledgement

The black pine specimens are the courtesy of Architect Cenk Senol, architect in charge of Tavsancil Carsi Mosque restoration.

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Tel: +90.312.294 30 00 - Fax: +90.312.294 30 88
E-mail: imo@imo.org.tr - www.imo.org.tr

ISBN: 978-605-01-0188-1
IMO Publication Nr.: E/11/12

Printing:
Mattek Matbaacılık Basın, Yayın Tanıtım Tic. San. Ltd. Şti.
Adakale Sok. No: 32/27 Kızılay / Ankara
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Preface

Throughout history territories of Turkey have been a cradle for many civilization; thus it is very rich in cultural and historical heritage. Protecting ages old historical structures against natural disasters should be priority issue for Turkey. Nations aware of this importance are striving through various scientific, social and cultural means, to make the new generations aware of the importance of historical structures and their safe transfer to the future generations.

Conservation of historical and cultural structures which have survived countless natural disasters for millennia can be achieved successfully by appropriate restoration, repair and strengthening applications. And this process can only be accomplished by collaboration of civil engineering and other disciplines concerned.

Civil engineering plays a major role in the restoration and rehabilitation of historical structures in the activities concerning soil-structure interaction, restoration design and material and construction techniques etc.

Being aware of its responsibility and its central role and also its conviction in the necessity of protection of historical structures, our chamber organised the symposium on "Strengthening of historical structures and their safe transfer to the future" in 2007, executed by TCCE Ankara branch. The second symposium with the same title was organised by TCCE Diyarbakır branch in 2009 with international participation.

Following the successful completion of the ECCE-WCCE-TCCE Joint Conference on "Earthquake and Tsunami" in 2009, the Presidents of the three organisations have agreed to organise the Second Joint Conference on As a result of the interviews with WCCE and ECCE after the conference on "Seismic Protection of Cultural Heritage". Our chamber considers this conference a step forward in its concern for cultural heritage bringing an international dimension to its activities in this area, during the 42nd term of office.

The major objective of this conference organised by our Chamber jointly with WCCE and ECCE is to contribute to the betterment of the seismic retrofitting and restoration practice on cultural heritage through disseminating the recent research results and communicating successful applications in our country and throughout the world.

Papers reflecting artistic and historical evaluation, conservation, seismic vulnerability assessment, seismic repair and strengthening, seismic monitoring etc. will be presented at the conference. We believe that the conference will be beneficial to our colleagues and also to those interested in this area and contribute to the protection of cultural heritage.

We would like to thank TCCE Antalya Branch for hosting the conference. We are grateful to Prof. Dr. Tuğrul Tankut, the chair of the Organising Committee for his endless efforts. We also thank the Organising Committee and the Scientific Committee for their contributions. We appreciate the valuable contributions of the keynote speakers and the authors of the papers. Lastly, we would like to express our appreciation and satisfaction for the contributions of our organising partners, WCCE and ECCE Executive Committees.

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