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ANALYTICAL INVESTIGATION ON THE USE OF FRP MATERIALS AS SEISMIC RESTRAINERS IN CONCRETE BRIDGES

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ABSTRACT

The present paper focuses on studying the use of fiber reinforced polymers (FRP) materials for limiting longitudinal displacements of concrete bridges under lateral earthquake loading. The targeted reduction of longitudinal seismic movements is achieved by applying FRP's sheets that can resist earthquake loading when activated in tension. The FRP restraining system is based on similar restraining systems that have been proposed by the authors in previous research works that involved the use of bundles of steel bars or prestressed unbonded tendons as restraining mechanisms either for design or retrofit purposes. The FRP's are installed in bridge sidewalks in orthogonal holes and the seismic forces are transferred to properly designed abutments. FRP's are advantageous as restrainers due to their durability, high strength and flexibility. An extensive parametric investigation including various carbon FRP properties, such as various moduli of elasticity, failure strengths, sizes, number of sheets and lengths was performed in order to demonstrate the applicability and effectiveness of the FRP materials as seismic restrainers. Nonlinear time history analyses were performed on a 3D finite element model of a benchmark monolithic concrete bridge and the influence of each parameter was investigated. Large reductions in the longitudinal displacements and in the pier seismic forces were the results of the analysis for seismic levels I and II. The improved seismic responses in combination with a rough cost analysis showed that the proposed restraining system is a highly efficient and economical solution for R/C concrete bridges.

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Analytical Investigation On The Use Of FRP Materials As Seismic Restrainers In Concrete Bridges

I. A. Tegos[1] and O. G. Markogiannaki[2]

ABSTRACT

The present paper focuses on studying the use of fiber reinforced polymers (FRP) materials for limiting longitudinal displacements of concrete bridges under lateral earthquake loading. The targeted reduction of longitudinal seismic movements is achieved by applying FRP's sheets that can resist earthquake loading when activated in tension. The FRP restraining system is based on similar restraining systems that have been proposed by the authors in previous research works that involved the use of bundles of steel bars or prestressed unbonded tendons as restraining mechanisms either for design or retrofit purposes. The FRP's are installed in bridge sidewalks in orthogonal holes and the seismic forces are transferred to properly designed abutments. FRP's are advantageous as restrainers due to their durability, high strength and flexibility. An extensive parametric investigation including various carbon FRP properties, such as various moduli of elasticity, failure strengths, sizes, number of sheets and lengths was performed in order to demonstrate the applicability and effectiveness of the FRP materials as seismic restrainers. Nonlinear time history analyses were performed on a 3D finite element model of a benchmark monolithic concrete bridge and the influence of each parameter was investigated. Large reductions in the longitudinal displacements and in the pier seismic forces were the results of the analysis for seismic levels I and II. The improved seismic responses in combination with a rough cost analysis showed that the proposed restraining system is a highly efficient and economical solution for R/C concrete bridges.

Introduction

Heavy damage on bridges in earthquakes, i.e. Loma Prieta (1989) and Kobe(1995), indicated the importance of designing them for structural integrity under seismic loading. EC Designer's Guide, [1], highlights that the prime decision for seismic design of bridges shall be the accommodation of the horizontal seismic displacements. EC8–Part 2 [2] includes provisions for designing bridges with control devices, such as bearings, dampers or seismic links that connect the deck with the abutments involving shear key arrangements, buffers, linkage bolts or cable restrainers. In the last decades, the use of restrainer systems in intermediate and outer expansion joints has been thoroughly investigated.

Conventional restrainer systems are most commonly used for bridge retrofit, aiming at limiting horizontal displacements induced by earthquakes at intermediate and outer joints [3]. They usually consist of steel cables or steel rods that can reduce relative hinge

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displacements when subjected to tension loading and prevent deck unseating. The seismic performance of these systems has been thoroughly investigated experimentally [4] and analytically [5], [6]. Design methods for the steel restrainers have been proposed from researchers [7], [8] and are also suggested by current code provisions [9]. Further research has been conducted regarding the enhanced behavior of restrainers by utilizing innovative materials, such as shape memory alloys, SMA's, [10]. Although, restrainers are considered as retrofit measures, they can be applied in bridge design as well, [11], and there has been ongoing research on their use instead of isolation or energy dissipation devices for preventing bearing failures during severe earthquakes, [12]. The authors studied in previous research work an alternative restrainer system, called struts-ties restrainers, for accommodating horizontal seismic displacements. The restrainers, STR's, consist of bundles of steel rebars that are placed longitudinally in the outer spans of the bridge deck through the abutments and receive both tension and compression loading and can be used in retrofit of existing bridges [13], and design of new bridges [14], [15], as well. On the light of the above, the present paper focuses on the investigation of the applicability and efficacy of an alternative restrainer system consisting of Fiber Reinforced Polymer (FRP) sheets in limiting the longitudinal movements of concrete continuous box girder bridges.

FRP materials typically consist of consists of high tensile continuous fibers oriented in a desired direction in a specialty resin matrix. Aramid, carbon, glass and steel fibers are the most common types of fibers used in the majority of commercially available FRPs. FRP systems that are used for structural applications, come in many forms including wet lay-up, pre-impregnated fiber sheets and pre-cured (composite sheets and shapes manufactured off-site),[16]. Indicative examples of conventional FRP applications are shown in Figure 1 where piers are retrofitted with FRP sheets for enhancing their deficiencies in concrete confinement, flexural and shear capacity through the development of tensile strains in the FRP material's fibers and the composite behavior of the structural member strengthened and the FRPs used [17]. However, in the present paper the response of the FRP sheets as tension members (restrainers) is utilized for the application of the proposed restraining system.

a) Carbon FRP jacket, source [16] b) Carbon FRP jacket

Figure 1. FRP Jacketing on Bridge Piers

FRP Restraining System

Description of the FRP restraining system and Structural Behavior

The proposed restraining system involves the application of FRP sheets on the superstructure of bridges in the longitudinal direction. Herein continuous concrete box girder bridges are studied. Similarly to the installation of the restraining systems of steel restrainers, [15], the FRP materials are placed at the outer spans of bridges extending through the abutments' wing walls. In Figure 2 schematic views of the proposed system are provided including a longitudinal bridge view, tha plan and cross section detail of the FRP mechanism. As it can be observed in Figure 2, the sidewalks at each side of the bridge are used as the installation position of the FRP sheets. Orthogonal holes are opened in the middle of the sidewalks and in their lower part in order to create the required space for the application of the FRP longitudinal sheets. The anchorage for each of the FRP groups is achieved by using bonding with epoxy and steel plates at the upper part of the cross section of the bridge deck at both the outer spans and the abutments wing walls while the rest of the FRP length is unbonded to the deck's and sidewalk's concrete. At all times, the forces developed by the FRPs shall be transferred through the anchorages to the structural members safely. Aiming on avoiding anchorage issues created it is suggested that the use of high performance concrete (i.e. emaco) is preferable in these vulnerable anchorage areas. Additionally, a safety factor of 1.20 can be adopted for the anchorage design.

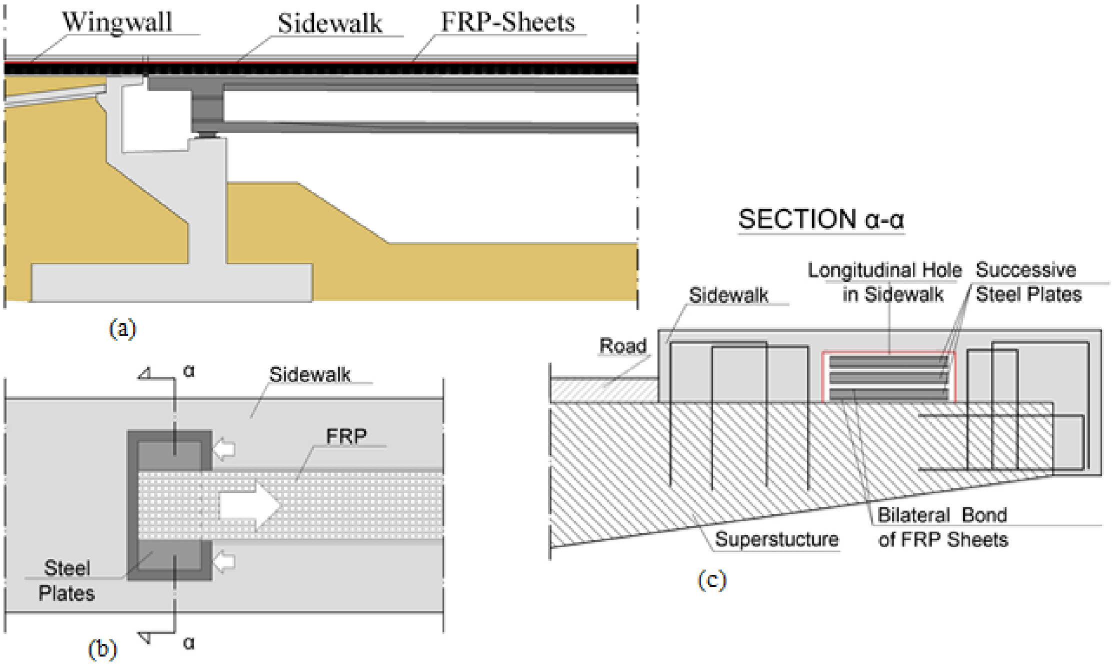


Figure 2. Schematic views of the FRP Restraining System. a) Elevation view abutment - outer span, b) Plan view sidewalk detail, c) Detail of the cross section of the deck

The mechanical behavior of the restraining system with fiber reinforced polymers has common characteristics to that of the steel restrainer system that has been proposed by the authors,[15,18]. As the FRPs are not bonded to the deck's or sidewalk's concrete and only anchored at their ends, they can behave as tension members under seismic loading. More specifically, FRP's are widely known for their capability of receiving high tensile forces, thus it is feasible under longitudinal movement induced by earthquake loading to develop tension that results in turning the FRPs into restrainers in the longitudinal direction. Although they receive tension forces, the FRPs do not receive compression loading leading to a reduced efficiency regarding the two longitudinal earthquake directions. However, the installation of the FRPs in both outer spans of the bridge allows the restraining mechanism to contribute to the bridge seismic response at all times by utilizing the tension developed to the FRPs at each side of the bridge depending on the change of signs of earthquake movement. The seismic forces received by the sheets (ties) are transferred to the abutments and activate them partially in contributing to the seismic response of the bridge. The use of fiber reinforced polymer sheets as restrainers can be characterized as advantageous considering their durability in time, as well. Several researchers, [19], have proven that FRPs suffer from minor deterioration. In addition, because of their elasticity they can accommodate minor transverse movements without resulting in brittle failures. Several types of FRP materials are used widely consisting of steel, carbon, aramid, glass fibers. Herein the investigation focuses on the use carbon fiber sheets. Two carbon fiber types that have wide commercial use were selected with the properties shown in Table 1, one with high and one with low elastic modulus of elasticity.

Table 1. FRP properties

FRP System	**Fiber Type**	**Weight [g/m2]**	**Thickness [mm]**	**Tensile Strength [MPa]**	**Tensile Elastic Modulus [GPa]**	**Strain at Failure [%]**
HEX 103C	Carbon	618	1.00	960	73.10	1.3
CarboDur S	Carbon	2240	1.30	2800	165	1.7

Design Objectives Identification and Seismic Compliance Criteria

The determination of the design objectives and the criteria that shall be accommodated are crucial for the system's structural behavior. Except from the seismic response, serviceability shall be taken into account as well. The service loads as defined by Eurocodes, [20], activate the ties restraining system. The FRP's are in tension during deck contraction and as a result tensile strains are developed. The design compliance criterion for the FRP's regarding the in-service loads is to keep those strains as low as possible so as to avoid any unexpected failures in the serviceability limit state. This criterion corresponds to a minimum acceptable FRP length that can be calculated by Eq. (1).

$$\Delta l = a \cdot \Delta T_{N,tot} \cdot \left[\frac{L_{tot}}{2} + L_{wingwall} \right] \qquad\qquad \frac{\Delta l}{l_{FRP}} = \varepsilon_{s\max} \tag{1}$$

where Δl is the deformation of the FRP sheet, a is the coefficient of thermal expansion, $\Delta T_{N,tot}$ is the component of the total uniform bridge temperature contraction, L_{tot} is the total length of the superstructure, $L_{wingwall}$ is the length of the FRP in the wingwalls. Their sum provides the total length of the sidewalks of the bridge. L_{FRP} is the length of the FRP sheets; ε_{smax} is the maximum allowable that is the maximum strain at failure reduced by a safety factor of 1.5 to allow for further deformation under additional earthquake loading.

The lateral forces induced by earthquakes in continuous box girder R/C bridges (ductile systems) are accommodated by the piers. The presence of the restraining system reduces the longitudinal seismic displacements of the bridge [15] and the seismic forces are redistributed. A part of the seismic forces is transferred through the FRP sheets to the abutments and the piers receive the rest of the seismic forces. In this manner, the abutments are activated and contribute to the seismic resistance of the bridge. The compliance criteria regarding the abutments induced in the design of bridges with the restraining mechanism include: the fulfillment of increased seismic resistance requirements of the abutments and the accommodation of stability issues. Although part of the seismic forces is transferred to the abutments, the piers continue to play a significant role in the seismic resistance. The compliance criterion regarding the design of piers in bridges that have the restraining system of struts-ties is to ensure that the piers receive forces lower than their failure and continue to high contribute highly to the seismic resistance. Clearly, when seismic demand pier moments approach or exceed the piers' yielding moments the ductility of the system can be utilized.

Benchmark Bridge and 3-D Model Properties

The Benchmark Bridge that was used for the extensive investigation of the FRP restraining system is a monolithic three span prestressed R/C bridge of Egnatia Motorway. The end spans are 45.10m and the middle span is 45.60m long and the total length is 135,80m. The deck consists of a concrete box cross section, connected to the piers rigidly and is supported on the abutments by sliding bearings, (Figure 3). The piers are circular with 2.0m diameter and are founded on 3x3 pile groups. The bridge's abutments are conventional seat-type abutments that provide the appropriate clearance, [2],between the deck and the back wall. The abutments restrain the transverse movements of the deck, since there are capacity design seismic links -stoppers installed on them. The bridge is founded on ground type B and the design ground acceleration in the area is 0.16g,[21].

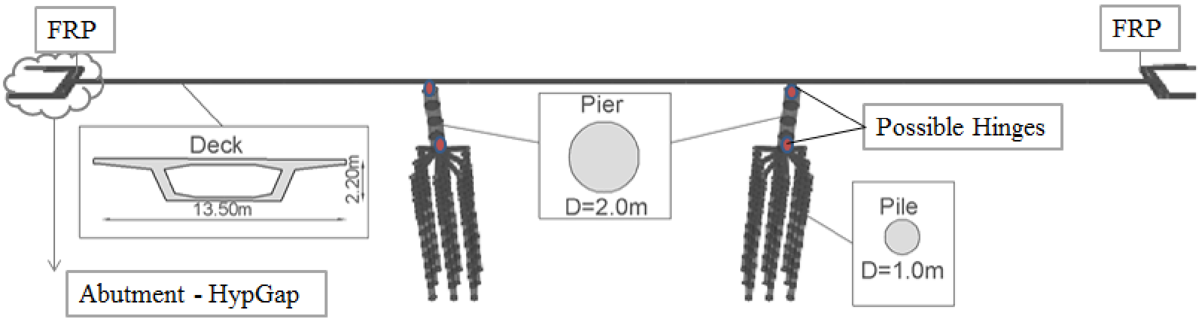
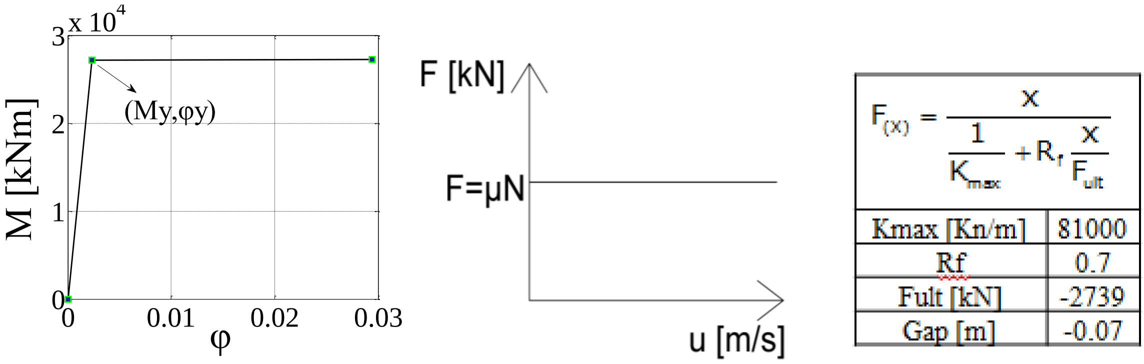


Figure 3: 3-D Opensees Bridge Model



$$F_{(x)} = \frac{x}{\frac{1}{K_{max}} + R_f \frac{x}{F_{ult}}}$$

Kmax [Kn/m]	81000
Rf	0.7
Fult [kN]	-2739
Gap [m]	-0.07

(a) (b) (c)

Figure 4: a) Moment - Curvature at Hinges, b) Sliding Bearing c) Abutment HypGap

The extensive investigation was performed on a 3-D finite element bridge model that was generated in the finite element analysis software OpenSees, [22], and accounts for soil-structure interaction. Figure 3 demonstrates the properties of one of the models including the FRP system, as well. The bridge components are modeled with frame elements taking into consideration material nonlinearities. The section analysis for the assignment of concentrated plasticity at the top and bottom of piers was performed with Bomber Biaxial v3.8.2,[23]. The Moment-Curvature plot at the plastic hinges is shown in Figure 4. Sliding bearing on the abutments have a low friction coefficient of $\mu=0.01$, Figure 4. The foundation springs were provided by the geotechnical report of the bridge. The passive resistance of the abutments due to the embankment mobilization when the gap at the expansion joints of the bridge was simulated according to Shamsabadi guidelines [24,25] and the HyperbolicGap compression only material was used in OpenSees, as shown in Figure 4c. The FRP sheets were modeled as elastic truss elements anchored at the appropriate position each time and responding elastically only in tension. Time-history nonlinear dynamic analyses were carried out with 7 independent pairs of recorded events taking the average of the individual responses as the seismic demand. The records were selected with REXEL 3.5 Beta [26] and they are compatible, their average spectra is compatible to Eurocode design spectra for 0.16g and 0.24g for soil type B.

Parametric Seismic Analyses and Results Discussion

The investigation of the performance of the suggested FRP restraining system requires extensive parametric analysis. The set of parameters included the possible FRP sheets characteristics. Two different types of carbon FRP's were selected and various lengths and numbers of FRP sheets anchored at each of the four wing walls, as presented in Table 2.

Table 2. Parameter Values

Parameters		**Values**
FRP	FRP Type	HEX 103C CarboDur S
	Length of FRPs	5-20
	Number of FRPs (0.30mwidth/FRP)	4-48
Seismicity	Seismic Level	I(0.16g) II(0.24g)

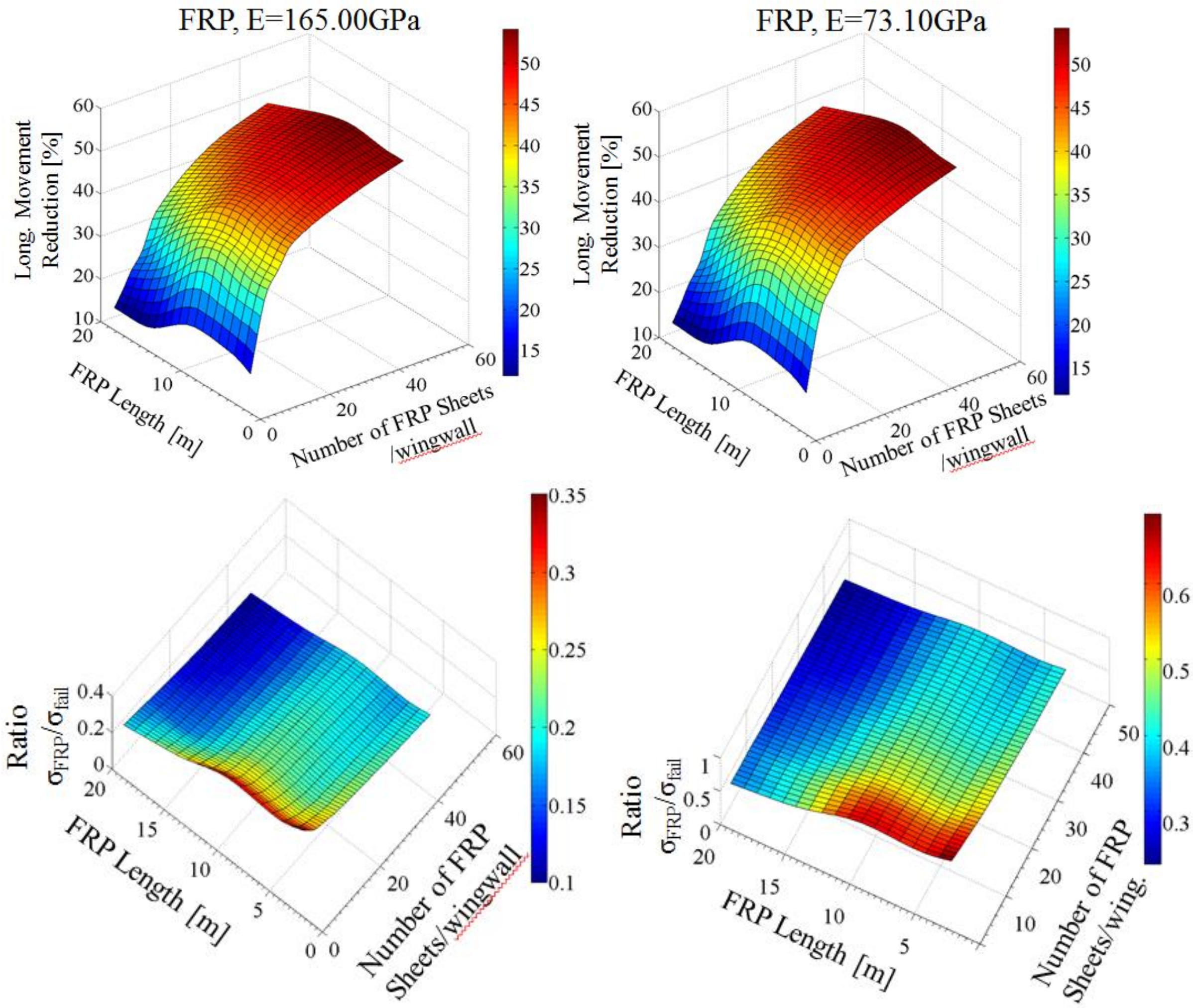


Figure 5: Bridge Response for two FRPs, High- Low Modulus of Elasticity, seismic level I

A fixed width of 30cm was assumed for all sheets for uniformity. All lengths selected accommodate serviceability limits requirements. Thus the minimum length selected was 5m for the FRP sheets. For smaller lengths, Eq.(1) is not satisfied resulting in deformations larger than the allowable. The inadequacy of short FRP's (<5m) to accommodate serviceability requirements excludes them from being utilized for seismic actions. Since the proposed restraining mechanism aims on limiting longitudinal movements and transfers part of the seismic forces to the abutments, at each FRP sheet selection it is ensured that the abutment configuration can receive the forces developed either under in service loading or under seismic loading. The presentation of abutment design procedures is beyond the scope of the present study. Regarding seismicity, all parameters were screened for the two seismic design intensity levels according to Eurocode 8, [1]. Seismic level I, which is the level of the bridge area and the following seismic level II were investigated.

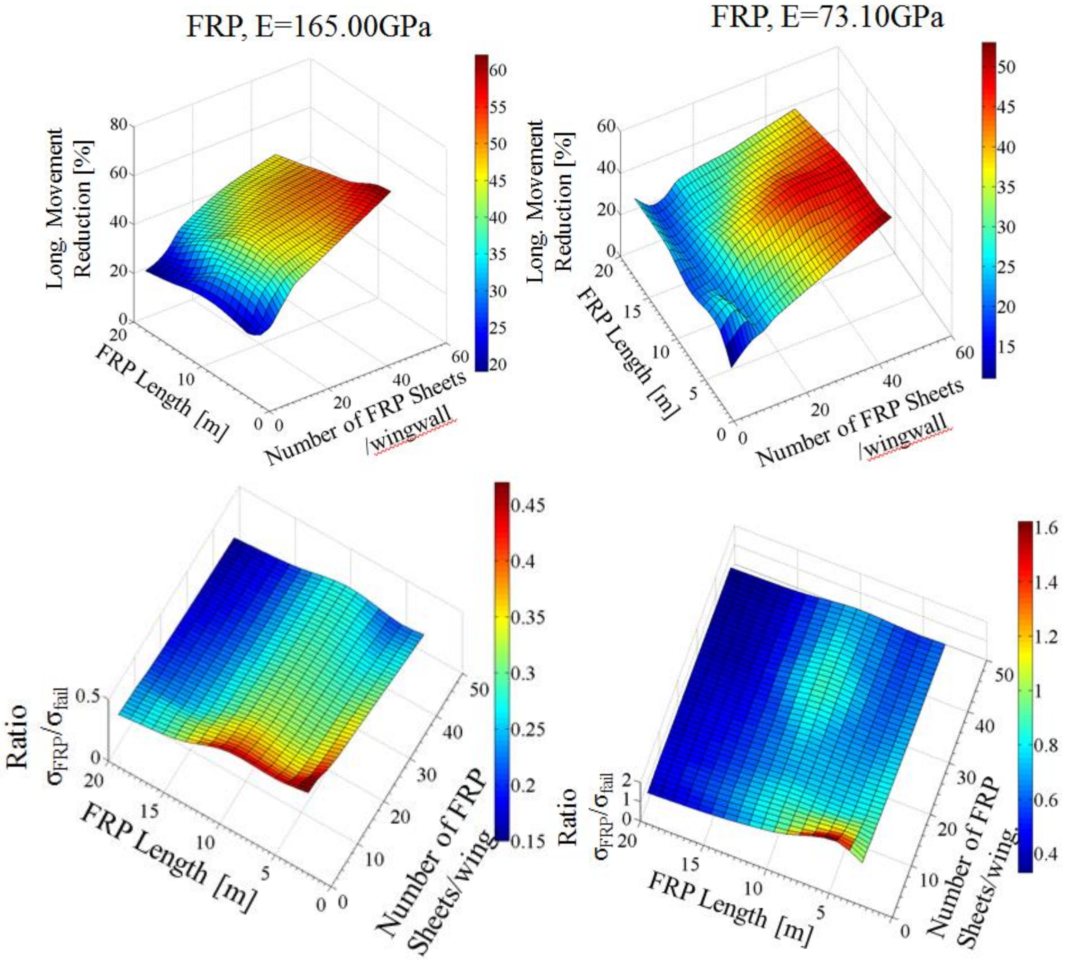


Figure 6: Bridge Response for two FRPs, High- Low Modulus of Elasticity, seismic level II

In Figure 5, the longitudinal movement reduction trends resulting by the application of various FRP properties are presented followed by ratio of the resulting maximum tensile stress on the FRP over the maximum stress at failure for seismic level I (0.16g) for the two carbon types. The x axis corresponds to the variable number of FRP sheets and the y axis to the length variation. It is observed that bridge performance depends primarily on the number of sheets used and secondly on their length. There are large reductions that arrive to 50% and 40% for 32 sheets - 5m long per wing wall for the Carbodur and the HEX103C, respectively. In addition, the maximum tensile stresses developed are lower than the failure stress for both fiber types. Especially, in CarboDur arrangements, the tensile stresses developed are lower than the 40% of its strength which means that although there are significant reductions, the available strength of 2800 MPa cannot be utilized and remains inactivated. Figure 6 demonstrates similar results for Seismic Level II. It shall be noted that even for seismic intensity 0.24g there are remarkable reductions in the longitudinal movements of the bridge. The Carbodur sheets do not reach high tensile stresses while regarding the FRP with the lower elastic Modulus, it can be seen that for sheet lengths below 10m and for arrangements with small number of FRPs (< 10) the maximum tensile forces are higher than the failure stresses, meaning that these arrangements are unacceptable for 0.24g seismic intensity. Therefore, FRP arrangements with larger number of FRPs are preferable, as the 5m-32 sheets which results in a 47% movement reduction. The enhancements on the bridge performance are not limited to the reduction in bridge longitudinal movements. As it can be seen in Figure 7, where the maximum pier moment and shear reductions by the activation of HEX103C arrangements for seismic level II are presented, are equally significant. The economy is another crucial factor for selecting optimum FRP arrangements. Rough estimations on the cost of the two carbon FRPs provided the results presented in Figure 8. The high cost of the Carbodur type arrangements reinforces the aspect of selecting the HEX103C type for the Benchmark Bridge. According to designer's data that was provided to the authors the actual cost of the bridge is 1,500,000€ without any restraining system. Therefore the cost of a feasible arrangement of 32 sheets – 5m long is lower than 1% of the total cost of the bridge.

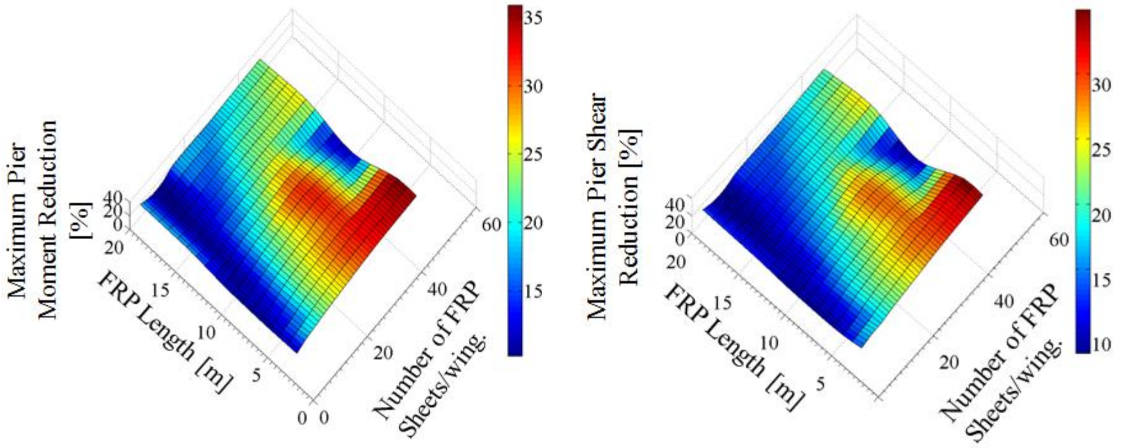


Figure 7: Moment and Shear reductions for piers with the application of the Low Modulus of Elasticity FRP type for seismic level II

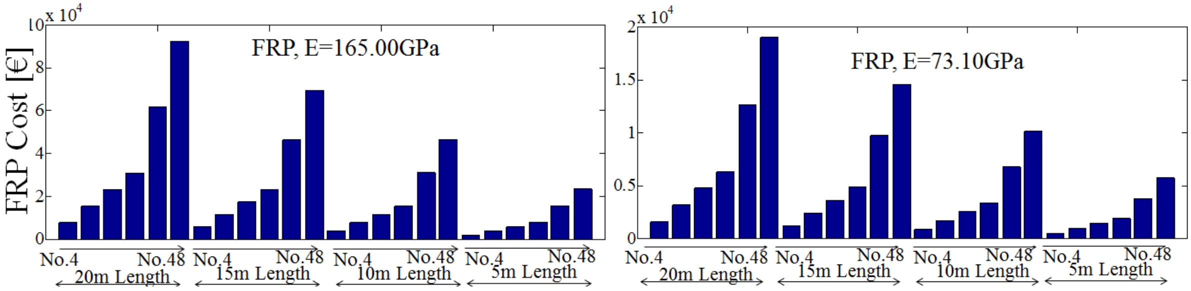


Figure 8: Total cost of the two carbon FRP type arrangements

Conclusions

The key objective of the present study is to propose an alternative restraining system of longitudinal bridge movements by using FRPs as tension members. The influence of various FRP parameters on the seismic response of continuous R/C box girder bridges has been investigated. The observations and data acquired from the conceptual design and the analyses for the applicability and efficiency of the proposed system are summed up in the following conclusions:

a) The proposed FRP restraining system improves the bridge seismic response by reducing largely the longitudinal displacements, pier moment and shear forces. Due to FRP materials high strength and deformability they can receive part of the seismic forces, transferring them through their anchorages to the abutments. The abutments are partially activated and contribute to the seismic response of the bridge.
b) The efficiency of the proposed system depends on the properties of the FRP sheets. The elastic modulus and the number of FRP sheets which affects the cross section area of the restraining system are the most influential parameter followed by the length of the sheets for both seismic intensities.
c) The proposed system is durable in time since it consists of the fiber reinforced polymers which have been found to present minor deterioration through their lifetime, especially compared to other materials as steel rebars. In addition, the high flexibility of FRP materials accommodates any issues that could arise by minor transverse movements.
d) The installation of the FRP system in the bridge sidewalks is highly advantageous. The sidewalks enhance the ease of constructability, inspection and replacement in case it is needed, i.e. after a severe earthquake.
e) The FRP restrainers can be considered as an economic solution due to the fact that they are materials widely available in commerce and durable.

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