Construction and Building Materials 170 (2018) 40–54

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Numerical-aided design of fiber reinforced concrete tunnel segment joints subjected to seismic loads

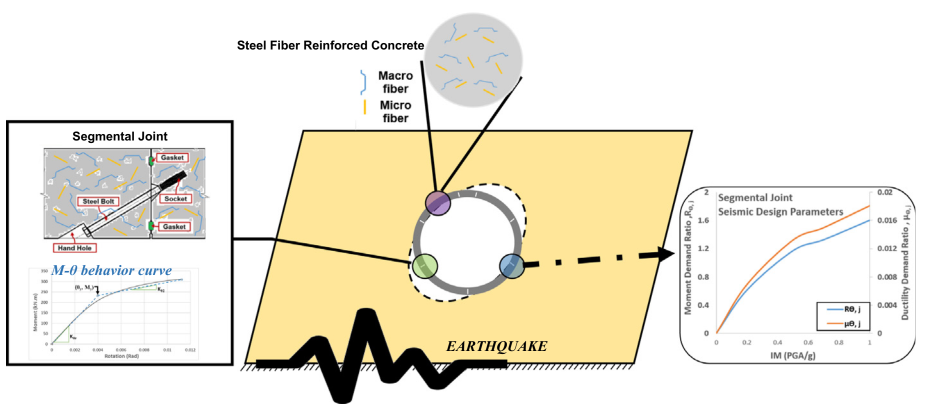
Mohammad Jamshidi Avanaki [a,*], Abdollah Hoseini [a], Shahram Vahdani [a], Albert de la Fuente [b]

[a] School of Civil Engineering, College of Engineering, University of Tehran, 14155-6457 Tehran, Iran
[b] Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC), C/Jordi Girona 1-3, C1-202c, 08034 Barcelona, Spain

HIGHLIGHTS

- Effect of Steel FRC on flexural behavior of segmental tunnel joints is studied.
- Micro steel fibers show more positive influence than macro fibers on joint behavior.
- Simple relations are proposed for seismic design of Steel FRC segmental joint.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 November 2017
Received in revised form 18 February 2018
Accepted 28 February 2018

Keywords:
Segmental tunnel
Segmental joint
Steel fiber reinforced concrete
Hybrid fiber
Seismic performance

ABSTRACT

In this paper, the effects of different steel fiber reinforced concrete (SFRC) composites on the flexural response of segmental joints under seismic actions is investigated numerically based on experimental results. The results in terms of moment – rotation (M–θ) curves derived from an experimental test set-up, are used to calibrate and verify a finite element numerical model of the joint. From seismic analyses, the SFRC mixes show to enhance the seismic performance of the joint compared to plain concrete or traditional reinforced concrete. Finally, equations are proposed to estimate the joint's moment demand/capacity ratio and rotational ductility for seismic design.

1. Introduction

In infrastructural development, tunneling projects generally consume a considerable amount of national budgets, justifying the need of more research focused on cost reduction and productivity enhancement methods. The use of fibers in cementitious composites has been introduced as a potential solution to increase productivity by cutting costs and saving time in tunneling projects [1–3]. Today, Fiber Reinforced Concrete (FRC) is commonly considered a suitable alternative to traditional concrete reinforcing solutions in designing structures for both SLS and ULS conditions [4]. In the past few years, the use of structural fibers as partial, or even full replacement of traditional reinforcement in segmental linings

* Corresponding author.
E-mail addresses: moh.jamshidi@ut.ac.ir (M. Jamshidi Avanaki), hosseiniaby@ut.ac.ir (A. Hoseini), svahdani@ut.ac.ir (S. Vahdani), albert.de.la.fuente@upc.edu (A. de la Fuente).

https://doi.org/10.1016/j.conbuildmat.2018.02.219
0950-0618/

of tunnel, has gained great interest in the tunneling industry [5–7]; particularly, after the realize of the Model Code 2010 [8], which gather bases to design FRC elements [7,9–11,1].

Structural fibers are produced from different materials (e.g., steel, polypropylene, glass, carbon). Likewise, various geometries (length, thickness, shape, anchorage) have been designed to meet specific technical requirements. Application of steel fibers has shown to improve the tensile post-cracking behavior of concrete composites by generating a crack-bridge mechanism to control crack width [12], resulting in more economic designs of structural elements, e.g. tunnel lining segments, generally designed in accordance with main standards [6,13,14]. Presence of fibers properly distributed [15] throughout the tunnel lining segment can significantly reduce detrimental consequences due to extreme loads from TBM jacks [16–18],fire exposure [19,20] or explosion [19,21].

In order to take advantage of the properties of each specific fiber geometry and composition, hybrid fiber reinforced concretes (FRCs) have been introduced [22,23]. In this sense, short fibers enhance the micro-cracking and cracking control within the range of SLS while longer fibers are capable to bear stresses even in ULS conditions [24]. In any case, the type and specifications of a fiber concrete mix is chosen to meet the target design requirements which requires experience and testing efforts [25,26].

Currently, segmental tunnels are widely used in seismic areas around the world, such as Mexico, Chile, Japan, Iran, the United States, and elsewhere. In such seismically active regions, the performance and vulnerability of infrastructure that can be subjected to earthquake loads, is of great concern. Despite being less vulnerable than above ground structures, minor to extreme incidents of damage to underground tunnels have been reported in past earthquakes [27–29]. It must be highlighted that tunnel deformations and water leakage, even reduced, can provoke severe damages to the structures above due to differential time-differed settlements. Therefore, for the reliable implementation of FRC in tunnel linings in such regions, extensive research on the seismic performance and vulnerability of tunnels linings is of paramount importance to guarantee the safety and integrity of the surrounding structures.

In segmented lining tunnels, the longitudinal joints, which connect the adjacent segments of each ring, also known as "segmental joints", have a significant effect on the global response [30–32]. Under seismic deformations in the transversal direction, segmental joints provide the necessary capacity for the tunnel section to accommodate the seismically generated ovaling deformations and other transversal distortions, playing an important role in preventing significant damage to the segment lining [32]. Despite the proved influence of the joint' properties on the tunnel response, for simplicity or uncertainties when assigning rotational stiffness, segmental joints are usually simplified as hinges in the design process by considering no flexural capacity [33]. Yet, research conducted on the behavior of segmental joints (plain type joint) indicate a semi-rigid flexural response [34,35], falling between the two extremes of perfect hinge (no bending bearing capacity) and fully rigid (continuous lining) configurations. In a segmental lined tunnel, transfer of load and bending moment between adjacent segments occurs due to interaction (contact) between the concrete segments, analogous to TBM jack load on segments, which the material resistant properties, the configurations and geometry of the jacks and thrust eccentricity strongly affects the joint' response [34].

El Naggar et al. [36] proposed a simplified analytical procedure to evaluate the in-plane response of segmented lining tunnels, considering linear elastic properties for the lining and simulating the segmental joints using a rotational stiffness. In a comprehensive study by He and Koizumi [37], the seismic response of shield tunnels in the transverse direction was studied with consideration of segmental joint effects. A series of shaking table model tests were carried out, followed by numerical simulations including 2D dynamic Finite Element Method (FEM), and static analyses based on the seismic deformation method by considering simple beam-spring model. The segmental joints were modeled using short beam elements with reduced axial and flexural rigidity in the static FEM analysis. In the beam-spring model, the segmental joints were modeled using a rotational spring with a constant value of rotational stiffness. The tunnel lining material was considered as linear elastic, defined by a modulus of elasticity. In a study by Chow et al. [38], the seismic in-plane response of a segmental tunnel lining was evaluated by a 2D FEM model; simulating the segmental joints as hinges. The authors concluded that a pseudo-static analysis could effectively reproduce seismically induced force demands in the tunnel lining. Do et al. [35] studied the influence of the segmental and longitudinal joints' properties on the overall 2D seismic response of segmental lining tunnels using a finite difference element model. This study indicated the dependency of segmental joints' behavior on surrounding soil conditions, segment configuration, and its material properties; emphasizing on the better performance of segmental tunnels over continuous lining tunnels under seismic loads.

Properties of the segment material have proven significant influence on the behavior of segmental joints, especially under seismic deformations [32,34]. Past research on segmental joint behavior has been mainly focused on plain or conventionally reinforced concrete as the segment lining material, generally modeled as a linear elastic material [30]. The safe and reliable application of fibers in segmented lined tunnels requires understanding the performance of its segmental joints, especially for tunnels constructed in seismic regions. In this regard, limited research has been conducted [39–42] to study the effect of FRC composites on the segmental joint behavior. Yet, an extensive lack of research exists considering different FRC composites with focus on seismic performance of segmental joints.

In this paper, an extensive numerical research on the flexural response of segmental joints in SFRC precast segmental linings subjected to earthquake loading is carried out considering the involved mechanical and geometric non-linarites. The main goal is to study the effects of different SFRC composites by comparing to that of unreinforced and conventionally reinforced concrete alternatives. These alternatives have been considered to be used in a particular segment geometry of the metro Line 7 of Tehran (Iran). To this end, six Hybrid Steel FRC (HSFRC) mixes comprising the use of different fiber combinations (0.3% and 0.5% volume content of micro and macro size) were investigated. Posteriorly, the post-cracking tensile behavior of these HSFRC composites was obtained by performing flexural 3-Point Bending Tests (3-PBTs) on notched specimens. As a result, stress-strain relationships were obtained for the HSFRC mixes by using the RILEM TC 162-TDF [43] specification. The suitability of these constitutive equations was confirmed using a numerical model capable to reproduce the 3-PBTs.

The experimental results [43] obtained from a test set-up designed for characterizing the mechanical response of segmental joints are used to confirm the accuracy of a non-linear FEM implemented to simulate the moment-rotation behavior of segmental joints. The model has been posteriorly used to derive curves for different HSFRC segmental joints. Finally, these relationships are assigned to the joints of the Tehran's Metro Line7 precast segments and 2D seismic analyses is carried out in order to obtain the mechanical behavior of the different parts of the ring. In this sense, the results derived are analyzed aiming at assessing and compare the vulnerability of the different HSFRC segmental joints. As a result, straightforward relationships are proposed for obtaining the flexural response of HSFRC segmental joints under seismic