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Seismic fragility curves for vulnerability assessment of steel fiber reinforced concrete segmental tunnel linings

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ABSTRACT

In recent years, application of fibers as a replacement for conventional reinforcement in segmented lined tunnels has gained great interest due to resulting cost and time savings. In seismically active regions, the seismic vulnerability of underground tunnels is of great concern. The aim of this paper is to investigate the effects of different composites of Steel FRC (SFRC), as the tunnel's lining material, on its seismic vulnerability, compared to each other and to that of unreinforced and conventionally reinforced concrete cases, employing analytical fragility curves. Results show that steel fibers, especially micro size fibers and for higher states of damage, display better seismic performance over conventional steel rebar in reinforced concrete linings. For best performance, a hybrid SFRC mix containing both micro and macro fibers, with a higher content of micro fibers over macro ones, is a technically preferable option for the design of segmental lining tunnels in seismic zones.

1. Introduction

In developing countries, underground railway networks, commonly known as 'subways', are rapidly growing in urban regions. Tunnels are the key elements in subway networks and considered as important national infrastructures and therefore, their requisition for public transport is of great interest. Tunneling projects consume a considerable amount of national budgets, signifying the necessity for more research on cost reduction and productivity enhancement methods in this regard. Using fibers in the concrete mix has been introduced as a potential solution to reduce costs and save times in tunneling projects (de la Fuente et al., 2012; Kasper et al., 2008; Burgers et al., 2007).

Fibers were employed to enhance the structural performance of hardened concrete under tensile and flexural actions, commonly known as Fiber Reinforced Concrete (FRC). Today, fiber reinforced concrete is widely used as a reliable design option in structures such as industrial pavement slabs, shotcrete of tunnels and in the precast industry (Mobasher, 2011). In the past few years, application of fibers as a replacement of traditional reinforcement for different structures under bending and shear forces, namely segmental linings of tunnel, has gained great interest (Buratti et al., 2013; Chiaia et al., 2009; Caratelli et al., 2011). Fibers of different materials (Steel, Polypropylene, Glass, carbon, etc.) and geometries (length, thickness) are used in fiber reinforced concrete. In recent years, research on simultaneously taking advantage of the beneficial effects of different types of fibers, by incorporating the different fibers into a single concrete mix, has led to the development of new cementitious materials, called hybrid FRCs (Banthia et al., 2000; Banthia and Nandakumar, 2003). The enhancement in engineering properties of hybrid composites, composed of two different fiber types has been shown in previous research (Mobasher and Li, 1996; Kakemi and Hannant, 1995; Xu and Hannant, 1992; Libre et al., 2011). In one type of hybrid FRC, different sizes of a single type (material) of fibers are combined. In any case, the type and specifications of a fiber concrete mix is chosen to meet the required conditions (Sorelli et al., 2005). In seismically active regions, the performance and vulnerability of infrastructure such as underground tunnels, under earthquake loads, is of great concern. Despite being less vulnerable than above ground structures, minor to extreme incidents of damage to underground tunnels has been reported in past earthquakes (Yashiro et al., 2007; FHWA/RD., 1981; Sharma and Judd, 1991). Therefore, for the reliable implementation of FRC in tunnel linings in such regions, extensive research on the seismic performance and vulnerability of such tunnels is vital.

In assessing the global seismic performance and behavior of structural elements, fragility curves play an important role. These curves plot the probability of exceeding a defined damage state at a certain

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value of seismic intensity. Fragility curves are a robust tool for evaluating the seismic vulnerability of structures. Various methods have been used to develop seismic fragility curves, including expert-based/engineering judgement, empirical, and analytical methods (Muntasir Billah and Shahria Alam, 2015; Kappos, 2016). So far, the fragility curves developed for underground structures, including tunnels, are generally based on engineering judgment, or obtained using tunnel damage data from past seismic events (ATC-13, 2001; FEMA and National Institute of Building Science, 2004), making its applicability limited. Fragility curves generated from analytical approaches can be readily applied to different structural configurations and seismic zones. These approaches have been mainly employed so far to develop fragility curves for building and bridge structures, barely implemented for segmented lining tunnels.

The aim of this paper is to evaluate the seismic performance of TBM constructed tunnels with Steel FRC (SFRC) precast segmental linings, using analytical fragility curves. The focus of this paper is to investigate the effects of different composites of SFRC, as the tunnel's lining material, on its seismic vulnerability, compared to each other and to that of unreinforced (plain), and conventionally Reinforced Concrete (RC) cases.

In this study, a comprehensive experimental program is initially conducted to acquire the mechanical properties of different SFRC mixes, primarily the post-crack tensile behavior. The mechanical properties of the SFRC composites are necessary in the numerical phase of the study to reliably model the behavior of the SFRC tunnel lining and calculate its response under seismic loading. For this purpose, the basic engineering properties of the SFRC composites are determined using compressive and splitting tensile strengths, and also flexural properties from 3-point bending tests (3PBTs).

Six concrete mixes, comprised of different combinations, using 0.3% and 0.5% steel fiber volume content of micro and macro size, is investigated. Hybrid Steel FRC mixes, i.e. combinations of micro and macro size steel fibers in a single concrete mix, are also investigated at a comprehensive level. As a result, stress-strain relationships are developed and validated for the SFRC mixes, using the RILEM TC 162-TDF (Rilem, 2003) guidelines. After completing the experimental phase, a procedure similar to previous analytical fragility studies (Argyroudis and Pitilakis, 2012; Pitilakis et al., 2014) is followed.

Underground tunnels are usually considered as non-redundant key elements in a lifeline network (transportation network, water supply network, etc.) which consume a considerable amount of time and capital for its construction. Therefore, any disruption in a tunnel's operation due to a seismic event, can potentially lead to catastrophic socio-economic losses and human fatalities. In this regard, application of new methods and materials for tunnel construction in seismically active regions should consider seismic safety and vulnerability aspects of tunnels. This study investigates the seismic vulnerability of SFRC segmental tunnels using fragility curves, providing a tool for city planners and disaster management authorities to evaluate the potential seismic vulnerability and damage of such tunnels against the economic savings of SFRC usage. Moreover, this paper helps better understand and compare the effect of different SFRC composites in segmental tunnel linings in the seismic performance of SFRC segmental tunnels, providing insight for the design of such tunnels in seismic zones.

2. Experimental program

Application of steel fibers has shown to saliently improve the tensile behavior of concrete composites by creating a crack-bridge mechanism to control crack width (Chiaia et al., 2007). This advantageous behavior of SFRC over conventional rebar has resulted in more economic designs of structural elements, generally designed in accordance with main standards (Liao et al., 2015). In large structural elements, such as tunnel lining segments, the usage of fibers in full/partial replacement of reinforcement bars can provide significant cost reduction and increase in production speed. Moreover, the proper distribution of fibers throughout the tunnel lining segment (Carmona et al., 2016) can significantly reduce spalling effects and detrimental consequences due to extreme loads from TBM jacks (Conforti et al., 2016; 2016), fire exposure (Colombo and Martinelli, 2015; Lilliu and Meda, 2013) or explosion (Colombo and Martinelli, 2015, 2016).

For the reliable implementation of steel fibers in a concrete mix, the main standards require experimental tests to determine the mechanical properties of SFRC. The obtained engineering properties are used as a basis to obtain the constitutive relationships of SFRC for describing the response under normal stresses. In this research, the mechanical properties of the SFRC composites are used in the numerical phase to reliably model the behavior of the SFRC tunnel lining and obtain its seismic response. In this regard, an experimental campaign is conducted using various mixes of micro and macro steel fibers, comprised of compressive, splitting tensile and 3-point bending tests (3PBTs).

Properties of the two types of steel fibers investigated are as follows:

- Macro fibers: Hooked ends, 50 mm length with 0.8 mm diameter.
- Micro fibers: Flattened ends, 13 mm length with 0.17 mm diameter.

The fibers used in this research are chosen due to their availability and current usage in fiber reinforced concrete applications in Iranian construction projects. In Table 1 and Table 2, properties of the fibers and corresponding volume content in each concrete mix are shown, respectively. The used fibers are displayed in Fig. 1. A plain concrete mix (mix No. 7) is also produced for comparison purposes. In Table 3, the materials and corresponding proportions used for the concrete mixes is given.

The mechanical concrete characterization was carried out by means of: (1) two 150 mm cubes for compressive testing at 28-days; (2) two 150 × 300 mm cylinders for the splitting tensile strength tests and (3) three 150 × 150 × 550 mm beams for the 3-PBTs over a span of 500 mm (Fig. 2). Cube and cylinder specimens were tested according to the ASTM standard (Annual book of ASTM standards, 1993) while beam specimens according to RILEM TC 162-TDF (Rilem, 2003).

Mean compressive (f_{cm}) and splitting tensile ($f_{ctm,i}$) strength values of FRC mixtures at 28 days along with slump values are listed in Table 4. The $f_{cm,\ 28}$ of plain concrete (mix 7) was about 40 MPa. The workability of fresh plain concrete, measured by the slump test, before addition of fibers was almost the same in all mixtures (in the range of 10–15 cm) but reduced significantly after addition of fibers, i.e. from 40 to 60% in different mixtures. Nevertheless, this reduction does not imply a problem in terms of production since high energetic vibration is induced in to the molds during the casting.

From the results gathered in Table 4, it can also be noticed, that both micro and macro size steel fibers increase the compressive and tensile strength of concrete mixes compared to plain concrete, up to

Table 1
Properties of fibers.

Fiber type	Geometry	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile strength (MPa)	Elasticity module (GPa)
Macro steel fiber	Hooked	50	0.80	62.5	1169	210
Micro steel fiber	Smooth	13	0.17	76.5	2100	210