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Simulation of crack propagation in prestressed concrete sleepers by fracture mechanics

S.M. Farnam, F. Rezaie*

Department of Civil Engineering, Bu-Ali Sina University, Hamedan, Iran

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ABSTRACT

Mode I crack propagation in prestressed concrete sleepers B70 is simulated by a fracture mechanics approach. The plastic damage model, which takes the non-linear behavior of concrete into account, is utilized to calculate crack length and crack mouth opening displacement (CMOD). Numerical data from prestressed concrete sleepers B70 under three-point bending load are compared with those of the proposed fracture mechanics model. In this study, fracture mechanics parameters of prestressed concrete sleepers are investigated. Sleepers with the length of initiation crack of 5 to 45 mm (with 10 mm steps) and the width of initiation crack of 2 to 8 mm (with 2 mm steps) are analyzed. Sleeper cracks are created in the notch and both of its sides. These analyses confirm that the structural behavior of prestressed concrete sleepers can be predicted by a simple fracture mechanics model provided that the related material properties like KIC, crack length and CMOD, are known.

1. Introduction

Sleepers are one of the main railway components, which receive the force from the wheels and convey it to the lines. In a railway structure, sleepers play a major role by conveying train axle loads to the underlying supporting ballast system [1]. The force is then transferred to the ballast layer while a constant spacing between the lines is maintained [2]. Different materials such as timber, steel, and concrete, with targeted life spans of 20, 50 and 50 years, respectively have been used as sleeper materials [3]. Timber sleepers are not common nowadays due to scarcity of wood sources that cause high price in some locations. However, this is not globally true and in many locations, concrete sleepers are more expensive. Steel sleepers on the other hand are not very common due to relatively high prices. Concrete materials are durable and have a good resistance to loading. Also, Comparisons of the mechanical properties of steel, timber and concrete sleepers indicate the optimum sleeper type based on railway structural and operational conditions is concrete sleepers [4]. Therefore using concrete sleepers has increased rapidly in international transition lines. Also, concrete sleepers are very inexpensive in comparison to timber and steel sleepers. By the development of railway lines and growing use of heavy and high-speed trains concrete sleepers have proven to be insufficient. Therefore reinforced concrete sleepers with high-strength materials are used to achieve high load capacity in railways. In the Iranian railways, prestressed concrete sleepers are more popular than the other types due to their high performance [5]. Railway sleepers are commonly made of prestressed concrete in the world as well [6].

Remennikov and Kaewuruen studied the static behavior of prestressed concrete sleepers with an experimental method considering the non-linear properties of the materials [7]. González et al. developed a failure analysis approach of sleepers and the ballast on which the tracks are laid. The aim of the study is to describe the method with which this type of failure should be analyzed [8]. In

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* Corresponding author.
E-mail address: frrezaie94@gmail.com (F. Rezaie).

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2012, Goangseup et al. investigated the failure of concrete railway sleepers under ice expansion [9]. Rezaie et al. have investigated longitudinal crack propagation in prestressed concrete sleepers B70 numerically and experimentally. The effects of extra pressure in screw anchor positions were simulated by applying cylindrical pressure inside the dowels holes and tested by an expanding material named Katrak [5].

The study of rupture and flow originated with Griffith's work on brittle solids such as glass [10]. Linear elastic fracture mechanics (LEFM) theory can probably describe fracture mechanics parameters such as fracture toughness, crack growth, load capacity and etc. for concrete. LEFM theory was used to investigate crack propagation and concrete fracture by Kaplan [11]. Shah and Mac-Garry investigated Griffith's criteria and showed that they are not an appropriate choice for concrete [12]. A large number of experimental and numerical studies are carried out on the fracture parameters of concrete elements, with different types or by various dimensions in order to calculate fracture mechanics parameters of the models [13–15]. Evaluation of the minimum reinforcement in the bridged crack model of concrete members has been examined experimentally and theoretically by Forveret et al. [16]. In 2011, Yahyaei-Moayyed and Taheri developed a finite element model (FEM) to simulate the prestressing process and to predict the creep response of an entire reinforced glulam system, including the PWCL, under an externally applied load and constant environmental conditions [17]. In 2011, Shauwyet et al. used an acoustic emission practice to find the fracture parameters of normal concrete [18]. Zhao et al. investigated the uniaxial tensile creep behavior of pre-cracked steel fiber reinforced concrete experimentally. Cylindrical specimens were pre-cracked at crack opening displacement (COD) for damage evolution [19]. Panfilov and Pischulev presented a theoretical and experimental analysis of deflections of reinforced concrete beams with allowance for discrete cracking in 2015 [20].

In the recent years, researchers have investigated fracture mechanics of reinforced concrete; however, very few of them have targeted prestressed concrete [5]. Rezaie and Farnam analyzed prestressed concrete sleepers based on the principles of fracture mechanics to evaluate fracture mechanics parameters such as KIc and crack growth [1]. In modern engineering design, fractural mechanics parameters of materials and structures are considered as the main design inputs. Although considering fracture mechanics of materials is very important, the sleeper fracture mechanics has not been taken into account in many of the current sleeper design codes (such as AREMA or UIC 713 and AS1085.14) [21–23]. This is because crack growth and resistance reduction of the structure are the main causes of losing serviceability conditions. Therefore, in this paper the emphasis is placed upon the numerical analysis of fracture mechanics of prestressed concrete sleepers B70. A purpose of the paper is to describe the propagation of cracks in a pre-stressed concrete element. There are three different loadings for crack growth analysis that result in three fracture modes: mode I fracture (Opening mode), mode II fracture (sliding mode) and mode III fracture (tearing mode). Mode I crack propagation or opening mode is a tensile stress normal (or tensile stress by bending moment) to the plane of the crack that is simulated by the plastic damage model in prestressed concrete sleepers B70 in this paper. Main fracture parameters of a notched prestressed concrete sleeper, such as the crack length and CMOD are calculated at the center and the sides. In our research team's inspection of Tehran-Karaj railway, crack and fracture was observed in sleeper's center and rail seat as shown in Fig. 1. Also, more research by Sadeghi [24] and Remennikov and Kaewunruen [25,26] is carried out on dynamic behavior of the sleepers (such as modal characteristics) and dynamic response of sleepers to train loads. Due to the current lack of standard codes of practice, the necessity of research in this field is evident.

2. Numerical model

2.1. Modeling

In this paper, the center negative three-point bending standard test is applied to a series of notched prestressed concrete sleepers B70 (Fig.2). In the majority of railway codes, 3-point-bending test is used for quality control. In fact, the behavior of prestressed concrete sleepers is very similar to beams and therefore it could be tested by three-point-bending test. The mentioned test with a notch is also used for other structures [27,28]. Loading conditions are applied based on negative center load test which is necessary in accordance to “AREMA Chapter 30” [29], “Australian Standard, and AS 1085-14” [30]. The typical geometrical dimensions of prestressed concrete sleepers B70 and the prestressed tendon arrangements are shown in Fig.3 based on the production line of Iranian

Fig. 1. Signaling gap in Tehran-Karaj railway.