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Strut effectiveness factor for reinforced concrete deep beams under dynamic loading conditions

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ABSTRACT

In a current study, a new strut effectiveness factor based on Strut-and-Tie Model (STM) is proposed to assess the ultimate shear strength of reinforced concrete (RC) deep beam subjected to dynamic loads. The derivation of the new effectiveness factor of concrete struts is based on Mohr–Coulomb criterion failure. Two types of concrete failure, diagonal splitting and concrete crushing failure modes, are proposed and examined. The modification of the proposed model is simulated in a MATLABSIMULINK environment. The proposed model exhibits efficiency in assessing dynamic shear resistance for deep beams. Moreover, a parametric study is then conducted to examine the effect of flexural reinforcement ratio, transverse reinforcement and shear-span to depth ratio on shear behavior of RC deep beams with consideration of the changes in strain rate. The proposed effectiveness factor is validated by utilizing the experimental results obtained from the literature and shows good accuracy for prediction the shear strength of reinforced concrete deep beams under different loading conditions.

1. Introduction

During their service life, reinforced concrete (RC) structures may suffer from various deteriorations, such as cracks, concrete spalling, large deformations, and collapse [5]. Such deteriorations are caused by several factors, including aging, corrosion of steel reinforcement, and environmental effects (earthquakes, impacts, and blasts) [11,14,28].

Under high loading rates the increase in the fracture energy and peak load are influenced due to the effect of inertia force. The strength and the elastic modulus of concrete were found to increase with the increasing the loading rates. Also the yield strength and the corresponding strain of steel increased with the increasing loading rates. To get proper design for all loading types, the studying of concrete behavior under wide range of strain rate (Fig. 1) is required [22].

Numerous studies have examined the behaviors of RC slender beams subjected to drop weight impact [18,19,23] and different loading rates [3,16,17,21]. According to the current design codes, such as ACI building code [1,2,8,10,13], a RC deep beam should be analysed utilizing the STM, which takes into consideration the complex stresses flow in D-regions. Based on the best author knowledge, studies on the ultimate strength and behavior of RC deep beams subjected to different loading rates are scarce. As a result, the necessity to modify methods for assessing the deep beams ultimate shear strength has become more significant in current literature topics. Therefore, this study aims theoretically to examine the ultimate shear

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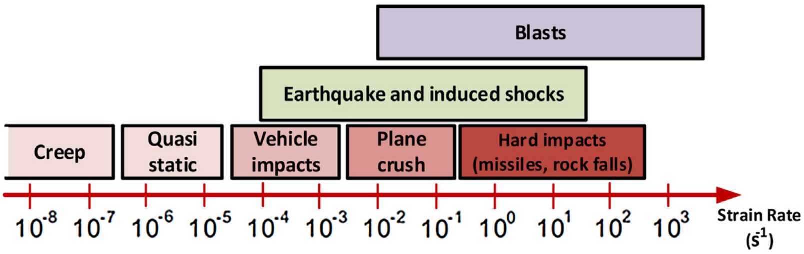

Fig. 1. Strain rate according to real loads [22].

capacity of RC deep beams under dynamic loading conditions, and suggests a new effectiveness factor which utilizes in the STM for designing of RC deep beams subjected to different loading rates. This factor plays a significant role in the STM design of RC deep beams and shear capacity prediction.

Various factors affect on the value of the effectiveness factor, for instance material properties, beam size, steel reinforcement, and structure loading. According to MacGregor et al. [20] the effectiveness factor ν differs from 0.25 to 0.85 based on the concrete strut in the plastic truss model utilized to estimate the deep beam capacity.

In the present study, the STM is extended to account for the ultimate shear strength of RC deep beams under varying loading rates. The proposed model considers the effect of the combined tensile strength of longitudinal and transverse reinforcements and the tensile strength of concrete. A linear failure criterion based on modified Mohr–Coulomb theory is adopted. A simple and refined interaction formula for predicting the ultimate dynamic shear strength of RC deep beams is derived. To imply and integrate the dynamic effect, the proposed constitutive relationships of concrete and reinforcing steel [16] are taken consideration. The proposed model considers the interaction between two failure modes, namely, diagonal splitting and concrete crushing of struts. A case study is also presented to verify the proposed method for deep beams subjected to varying loading rates. The analysis results indicated a good accuracy for prediction the ultimate shear strength of RC deep beams under dynamic loading conditions.

1.1. Research significance

Limited information has been recorded on RC deep beams subjected to dynamic loads in literature. Moreover, the previous proposed STM approaches for RC deep beams and design equations used for slender beams, are mostly over or under estimation due to it is empirical nature. A new strut effectiveness factor for deep beams under different loading rates is proposed, with a refined STM which used to assist in the appropriate design of such members.

1.2. Limitations and assumptions of the proposed model

To develop the applicability of the STM concept for RC deep beams under dynamic loads, the following assumptions and limitations are made:

- The proposed model is confined for simply supported RC deep beams.
- A uni-axial compressive stress f_2 (Fig. 1) is applied to the concrete strut which inclined at an angle q with respect to the beam axis;
- The failure of shear tension caused by the inadequate anchorage of flexural reinforcement is not considered.
- The proposed model considers the effect of crushing and diagonal splitting concrete failure.
- The proposed model implies the dynamic effect by considering the constitutive relationships of concrete and steel reinforcement which proposed by Fujikake et al. [16]
- The proposed model implies iterative procedures to calculate the ultimate strength of deep beams under dynamic loading conditions.

2. Stress–strain relationships of concrete and steel reinforcing under dynamic loading

*2.1. Material **model for concrete***

Concrete materials are sensitive to changes in strain rates. Under dynamic loading rates, both tensile and compressive concrete strengths significantly increase. In the current study, the strain effect, which can be accounted by utilizing a Dynamic Increase Factor (DIF). The DIF values proposed in the literature Fujikake et al. [16] are used for both concrete and steel materials. Fig. 2 shows the constitutive relationships for the stress–strain of concrete and steel reinforcement [16].