Engineering Fracture Mechanics 94 (2012) 1–12

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

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

Three-dimensional cohesive crack model prediction of the flexural capacity of concrete slabs on soil

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ARTICLE INFO

Article history:
Received 27 September 2011
Received in revised form 19 April 2012
Accepted 24 April 2012

Keywords:
Flexural capacity
Concrete slab
Fracture mechanics
3-D cohesive elements
Elastic foundation

ABSTRACT

A three-dimensional approach to discretely account for crack initiation, crack growth, and determination of the flexural load capacity of concrete slabs on an elastic foundation under mode I loading is proposed. The finite element model incorporated cohesive crack elements along a pre-defined crack path in the concrete slab. A bilinear softening model was used to describe the stress-crack opening relationship for plain concrete and was defined solely on measured strength and fracture properties. The proposed method predicted the slab's flexural load capacity as compared to the large-scale experimental concrete slab results for several geometries and notch configurations. The model also provided insight into stress concentration areas and crack propagation positions at different load levels.

1. Introduction

Concrete pavement design continues to evolve, especially in the types of inputs and slab stresses considered and the ability to accumulate fatigue damage in small-time increments [1]. However, one of the weakest components of mechanistic–empirical (M–E) design techniques [1,2] is still the concrete fatigue relationship, which generally requires an additional calibration function to match the observed field performance. Experimental research [3–6] has shown that concrete slabs under fatigue loading sustain greater stress ratios and higher cracking resistance than that predicted by concrete beam fatigue curves cast with the same material. This phenomenon has also been observed in plain concrete slabs [7,8], fiber-reinforced concrete slabs [9,10], and full-scale continuously reinforced concrete pavement sections [11]. To more accurately predict the fatigue life of the concrete slabs, Roesler and Barenberg [12] proposed an alternative method to calculate the stress ratio to be used in conjunction with existing fatigue curves. Their approach consisted of using the static flexural strength of the slab instead of the beam flexural strength and redefining the stress ratio as the quotient between the applied tensile stress in the slab and its monotonic strength (flexural load capacity). This approach differs from current methods, which calculate the stress ratio as the quotient between the tensile stress in the slab versus the concrete flexural strength from a simply-supported beam configuration.

The existing limitation to this approach has been how to determine the flexural capacity of a soil-supported slab without running an experimental slab test for each geometric, boundary, and load configuration. Recently, Roesler et al. [6] calculated the load capacity of 1.8 by 1.8 m concrete slabs on soil using flexural beam strength tests (modulus of rupture) and compared

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0013-7944/$ - see front matter
http://dx.doi.org/10.1016/j.engfracmech.2012.04.029

Nomenclature

SEN(B)	single-edge notched beams
G_F	total fracture energy
G_f	initial fracture energy
CMOD	crack mouth opening displacement
$CTOD_C$	critical crack-tip opening displacement
K_{IC}	critical stress intensity factor
E	concrete modulus of elasticity
f_t'	splitting tensile strength of concrete
ψ	kink-point stress ratio
t^0	damage initiation point
δ_f	final crack opening width
RAC	recycled aggregate concrete

these values to the experimental load capacity of the full-scale slabs. The authors found that, on average, the experimental load capacity of 150 mm-depth slabs was approximately 50% higher than the slab load capacity assuming the maximum tensile stress in the slab cannot exceed the beam flexural strength. This difference increased to 180% when 90 mm-thick concrete slabs with 0.4% macro-fibers were used. The interactions between slab geometry, boundary condition (soil foundation), and concrete fracture properties are the main reason for the discrepancy between slab capacities predicted based on simply-supported concrete beam properties and actual slab test results.

To adequately account for the crack propagation, concrete slab failure capacity, and known concrete size effect, fracture mechanics principles must be used to couple the concrete material's failure response with the specimen geometry, loading, and boundary conditions. While the application of fracture mechanics to predict the failure response of concrete materials is not a recent research topic, there have been extensive studies over the past 30 years on the use of fracture mechanics to describe the crack propagation and failure of a variety of specimen types, e.g. [13–16]. Likewise, there has been an increasing interest in applying fracture mechanics to solve pavement engineering problems over the past 20 years [17–26].

One successful approach used by numerous researchers to describe the fracture behavior of small-scale concrete specimens has been the implementation of the cohesive crack model into finite element codes [27–37]. The cohesive crack element represents the quasi-brittle behavior of plain concrete under tension and has been shown to be adequately represented by a bilinear softening curve [15,38]. Recent research [38–40] has demonstrated that the bilinear softening curve for concrete materials can be entirely defined by four properties measured in the laboratory: the total fracture energy [41], G_F; the initial fracture energy [42], G_f; critical crack-tip opening displacement [40], $CTOD_C$; and the tensile strength of concrete, f_t', determined by the ASTM C496 split tensile test. This defined cohesive element was verified on three-point bending tests of single-edge notched beams, SEN(B), made with plain concrete of different depths [38], fiber-reinforced concrete [39], and functionally-graded concrete materials [43,44]. Gaedicke and Roesler [45] also successfully predicted the load–deflection response of 2-D and 3-D concrete beam specimens on an elastic foundation using the same cohesive crack element. Ioannides et al. [22] had earlier published load–deformation results from 3-D finite element modeling of concrete slabs on an elastic foundation. However, their results did not demonstrate lower post-peak loads and the same level of softening seen in previous experimental results [3,5,9]. The literature lacks a validated procedure which uses a realistic 3-D model to account for the effect of the softening behavior of concrete with measured concrete slab response data and its expected influence on the flexural capacity of concrete slabs on ground.

This paper aims to quantify the crack propagation and flexural capacity of concrete slabs on elastic foundation using 3-D fracture-based finite element analysis by defining the concrete material failure from standard fracture and strength tests. The results predicted by the 3-D finite element fracture model will be validated with large-scale experimental concrete slab results. The fracture-based finite element approach will assist in better characterizing the influence and interaction of the concrete slab geometry, concrete fracture properties, crack geometry, and existing boundary conditions on the slab's flexural capacity.

2. Experimental program and results

2.1. Experimental program

Small-scale beams were cast for characterization of the concrete material fracture properties while large-scale slab tests were used to validate the 3-D finite element fracture model. The laboratory program, shown in Table 1, involved casting 2000×2000 mm slabs with two thicknesses (63 and 150 mm) and notch types (edge and one-third) to be tested monotonically on a soil foundation. The edge-notch specimen had a full-depth 400 mm notch at the mid-slab edge as shown in Fig. 1b. The one-third notch specimen had a notch that extended across the bottom of the slab with an initial length of one-third of the slab depth, as shown in Fig. 1c. The slab size was determined by the available large-scale testing equipment, and the notch types were representative of idealized crack configurations for testing and modeling.