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Modal characteristics of cracked thin walled unsymmetrical cross-sectional steel beams curved in plan

Palash Dey, S. Talukdar*

Department of Civil Engineering, Indian Institute of technology Guwahati, Guwahati 781039, India

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The paper aims to develop a generalized Finite Element (FE) model for multiple cracked thin-walled curved beams by taking account of the warping effects in the cracked section. Modal features such as natural frequencies and mode shapes for cracked and uncracked curved beam have been presented for sections having one axis of symmetry and with no axis of symmetry for various crack parameters. Theoretical results have been validated by laboratory vibration test on steel channel and angle section beams. The study reveals that cracked curved thin-walled beams behave differently under vibratory load compared to that with straight beams.

1. Introduction

Damage or crack is a physical discontinuity in a material or an object. It may be developed either during manufacturing or service stage. In real field applications, ranging from outer space to the deep ocean, various engineering structures such as buildings, bridges, towers, turbine, helicopter and propeller blades are frequently subjected to numerous dynamic excitations in complex environment which may lead to the vibratory behaviors of the structural system. It needs to be mentioned that damage forming cracks rapidly propagate under repeated and reversal loading. Therefore, it is of particular importance to detect the early stage of crack so as to ensure reliable, safe and lasting structural performance on repair and retrofitting. The significant step in structural health monitoring of an engineering structure is the appraisal of its modal characteristics, such as natural frequencies and mode shapes. This modal information plays a key role in the vibration based health monitoring of the structures.

Chaix et al. [1] investigated damage in concrete using back-scattered ultrasonic waves. Rahani et al. [2] demonstrated that the ultrasonic waves are not very effective in detecting internal defects in some materials such as ceramic foam tiles. Reference [3,4] presented the structural health monitoring technique using acoustic emission. The image based damage detection for cable surface in cable stayed bridge can be found in Reference [5]. However, all these non-destructive testing need the location of crack be known a priori and that the portion of the system under inspection be easily accessible. These limitations led to the improvement of global monitoring procedures based on changes in the vibration characteristics of the structural or mechanical system. Detailed review of the damage detection methods based on vibration can be found in [6–9]. Messina and Jones [10] presented the damage location assurance criterion, which was used to localize the damage in the structures. Modal assurance criteria (MAC) and coordinate modal assurance criteria (COMAC) have been considered by Wolf and Richardson [11] and Ndambi et al. [12] to estimate the level of correlation between two different mode shapes. Friswell and Penny [13] compared the different approaches to crack modeling for beam structures. Changes in the eigen parameters are considered to determine the location and extent of damage by Yuen [14]. Absolute changes in the curvature mode shapes have been used by Pandey et al.[15] to detect damage or crack present in a beam. Hu et al.[16] carried out the damage assessment of a structure based on modal test data. Dutta and Talukdar [17] have considered Lanczos algorithm for eigen analysis for accurate assessment of modal parameters to diagnose damage in bridge structure. Darpe et al. [18] studied the coupled vibrations of a cracked rotor. A model-based algorithm, in order to locate and quantify the size of a crack, based on free vibration measurements of a cracked beam can be found in ref. [19]. Kisa et al. [20] employed a combination of finite elements and component mode synthesis methods to estimate the presence of crack in circular beams using free vibration analysis. Nguyen [21] studied the *mode shapes of a cracked rectangular cross sectional beam using finite element method.* Agarwalla and Parhi [22] studied the effect of crack on modal parameters of a cantilever beam subjected to

* Corresponding author.
E-mail address: staluk@iitg.ernet.in (S. Talukdar).

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vibration. Mode shape curvature based damage detection can be found in refs. [23,24]. Madhavan et al. [25] describes the problems concerning damaged turbine rotor blade vibration using experimental studies. Sampaio et al. [26] used operational deflection shapes as damage detection indicator. Ricci and Viola [27] and Viola et al. [28] conducted a study on cracked T-section beams by excluding warping effects. It is found that most of the approaches mentioned previously has been extensively used the line spring element [29–33] in finite element analysis of cracked beam sections. However, in those methods researchers excluded warping deformation in crack modeling.

Thin-walled beams are widely used in aerospace engineering, civil and mechanical engineering as principal load carrying members. They are often curved for architectural reason or due to space constraints. According to Vlasov [34] the ratio of thickness of the beam to any characteristic dimension of the cross-section (its width or height) or any characteristic dimension of the cross-section to its length is less than equal to 0.1, then such type of beam comes under thin-walled beam categories. Several theoretical studies on uncracked thin-walled straight beams for different configurations are available in refs. [34–41]. El-Amin [42] studied the horizontally curved beam using finite element including the effect of warping. However, this finding will not be applicable for cracked thin-walled beams. Hsu et al. [43] developed a more exact horizontally-curved beam element. Yang et al. [44] studied the dynamic response of a horizontally curved beam subjected to vertical and horizontal moving loads. A curved beam theory based on centroid-shear center formulation has been demonstrated by Kim and Kim [45] for the spatially coupled free vibration. Yoon et al. [46] studied the horizontally curved steel 'I' cross-section beams and effects of natural frequencies on such type of beams. Spectral finite elements (SFEs) are developed for wave propagation analysis of isotropic curved beams by Nanda and Kapuria [47]. These available literatures do not fit to the mechanics of cracked or damaged thin walled beams. Krawczuk and Ostachowicz [48] studied the natural vibrations of a clamped-clamped arch with an open transverse crack. Viola et al. [49] applied the analytical and differential quadrature method for vibration analysis of damaged circular arches. Öz [50] investigated the in-plane vibrations of slightly curved beams. Karaagac et al. [51] demonstrated the effects of crack on the in-plane static and dynamic stabilities of a circular curved beam with rectangular cross-section excluding the effects of warping in crack modeling. Literature survey shows that the most of the researchers have studied damage detection techniques based on vibration responses to diagnose the cracks in solid beams of doubly symmetrical cross-section such as circular, square, rectangular and tubular using the knowledge of modal parameters. To the best of the authors' knowledge, modal features in thin-walled curved beams considering warping effects with one axis of symmetry and with no axis of symmetry have not been studied prior to the work presented in this paper.

In the present work a generalized finite element model for multiple cracked curved beam is developed including the warping effects in the cracked model. The local flexibility approach is considered to model the crack based on linear fracture mechanics and the energy principles. The crack is assumed to remain always open. It is also assumed that the crack affects only stiffness of the beam whereas the mass remains unchanged. Two types of beams (i) with one axis of symmetry (Channel cross-section) and (ii) with no axis of symmetry (Angle cross-section) having horizontally curved profile have been taken up in the present study. Modal characteristics of beam specimen with different subtended central angle (θ_s) and of different crack parameters have been presented conducting a through theoretical and experiment study.

2. Finite element formulation

An arbitrary cross-sectional thin-walled horizontally curved beam with n number of cracks has been shown in Fig. 1(a), where L is total span of the beam. Cracks are placed at the distance L_{C1}, L_{C2} … L_{Cn} from one end of the beam respectively and R is radius of the curved beam. In this figure the mass and shear center are represented by CG and SC respectively. The cross-section of cracked beam portion has been shown in Fig. 1(b), where a is maximum crack length. Fig. 2(a) and (b) depicts the cross-section of cracked

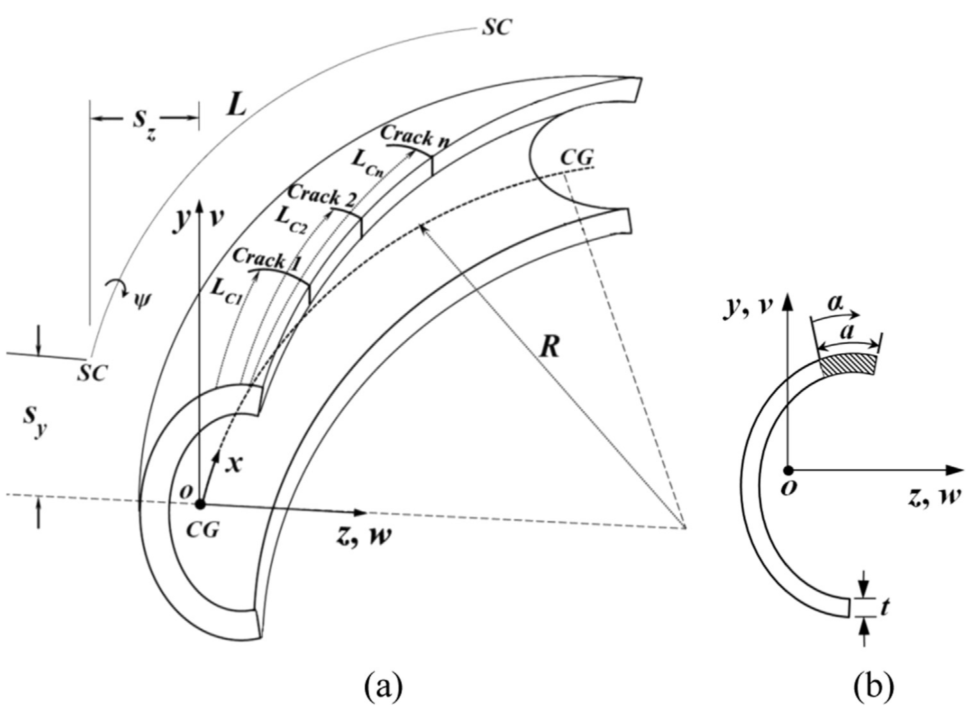

Fig. 1. Horizontally curved beam of arbitrary cross-section (a) Longitudinal view, (b) Cross-sectional view.