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Numerical buckling analysis for flat and cylindrical shells including through crack employing effective reproducing kernel meshfree modeling

M. Ozdemir[a], S. Tanaka[b,*], S. Sadamoto[b,1], T.T. Yu[c], T.Q. Bui[d]

[a] Department of Naval Architecture and Marine Engineering, Ordu University, Turkey
[b] Graduate School of Engineering, Hiroshima University, Japan
[c] Department of Engineering Mechanics, Hohai University, China
[d] Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Japan

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ABSTRACT

Buckling behavior of flat and cylindrical shells including through-the-thickness crack (through crack) is examined employing an effective reproducing kernel (RK) meshfree method. The concept of convected coordinate system is adopted to deal with general curvilinear surfaces. Both field variables and shell geometry are approximated by RKs, which is conceptually same procedure with isoparametric Finite Element Method (FEM). Each node has five degrees of freedom (DOFs). The numerical integration of stiffness matrices is conducted by strain smoothing approaches. In the present study, a crack modeling is introduced into the curved shell geometry for analyzing cracked cylinder buckling problems effectively. The presented approach has an attractive feature, i.e., five DOFs cracked flat shell model is only required for analyzing three-dimensional (3D) cracked curved shell problems. The accuracy and effectiveness of the present method are critically examined through several numerical examples in which the obtained results are compared with reference solutions as well as with the results of commercial FEM package (ANSYS). Effects of the element types in the FEM computations are also examined by comparison of the results by linear and quadratic shell elements. The results shed light on the significant effects of considered configurations on buckling coefficients and mode shapes.

1. Introduction

Ship and offshore structures are often composed of plate and shell assemblies. They are usually designed in effective ways to provide higher structural performance during service life as well as for straightforward inspection and maintenance. The authors have studied buckling and ultimate strength of stiffened plate structures [1,2] and ship's hull [3]. Some manufacturing operations such as welding or extreme variations in environmental conditions may generate defects, e.g., through cracks, which might have detrimental effects on the integrity and load bearing capacity of the structures. These defects can sometimes be repaired by maintenance, however it is not always an easy task to inspect and alleviate the defects. It is therefore necessary to predict the performance and integrity of cracked structures. Buckling phenomenon is related with structural stability. Although intact structures may buckle globally, buckling may take place locally near the crack due to higher stress gradients caused by discontinuity. Buckling phenomena are one of the main subjects to the scientific and engineering community, and they have been studied by many researchers using different approaches. This particular work however is devoted to the numerical buckling analysis of imperfect flat and cylindrical shells, but using a novel effective meshfree method.

Since last few decades, critical examination of cracked plates and shells has considerable interest employing analytical methods [4], semi-analytical methods [5,6], experimental methods [7–9], FEM [10–19] and extended FEM (XFEM) [20–22]. Vafai and Estekanchi [10] conducted parametric FEM computations on the buckling of cracked plates and shells. Meshing pattern on the crack tip, boundary conditions (BCs), Poisson's ratio and shell curvature were considered as parameters affecting structural performance of the cracked flat and curved shells. Brighenti [13] studied the buckling behavior of thin plates under compressive and tensile loads. Aside to crack parameters, effect of Poisson's ratio was also examined since Poisson's ratio becomes a significant parameter under tensile loading condition. Khedmati et al. [15] carried out a series of parametric study to examine the effects of crack parameters on the buckling behavior of continuous ship plates. In the paper, crack location was also considered as a parameter affecting

* Corresponding author.
E-mail addresses: muratozdemir@odu.edu.tr (M. Ozdemir), satoyuki@hiroshima-u.ac.jp (S. Tanaka), sadamoto.shota@jp.fujitsu.com (S. Sadamoto), tiantangyu@hhu.edu.cn (T.T. Yu), bui.t.aa@m.titech.ac.jp (T.Q. Bui).
[1] Present address: Fujitsu Limited, 9-3, Nakase 1-chome, Mihama-ku, Chiba city, Chiba, 261–8588, Japan.

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structural performance of the plate. Seifi and Khoda-yari [16] examined the buckling characteristics of central-inclined cracked plates conducting both experimental and numerical studies. Influences of crack length and orientation as well as plate thickness and edge conditions on the buckling behavior were examined. Estekanchi and Vafai [11] analyzed buckling problems of cylindrical shells under compression and tensile loads for different crack sizes and orientation angles. Special mesh zooming technique was employed on the crack tips instead of using special kind of tip elements. Then, Javidruzi et al. [12] considered fine mesh not only for crack tip but also crack segment for the both buckling and dynamic analysis of cracked cylindrical shells. It was also indicated that when the crack length is relatively small, the effect of fine mesh along crack segment becomes visible on buckling load. Buckling problems of cracked functionally graded cylindrical shells were recently addressed by Nasirmanesh and Mohammedi [22].

Based on the aforementioned facts, it could be said that the FEM was mainly adopted for the modeling and analysis of cracked shell structures. Linear shell elements are usually preferable for the modeling and analysis of ship and offshore structures owing to the less computational expense compared to higher order elements. On the other hand, adopting linear elements for the approximation and analysis of curvilinear surfaces may sometimes cause shear locking phenomenon. Fortunately, it is possible to see vital improvements in the element formulation and discretization, see Refs. [23,24]. Meshfree methods and other related methods can overcome shear locking problems owing to higher order approximation functions. They are therefore popular for solving boundary value problems, *e.g.*, intact problems for isotropic [25–29]; composite [30–32] and functionally graded materials [33–35] and cracked problems [36–38] were handled. Isogeometric Analysis (IGA) [39] is recently emerged popular method and can be employed for predicting structural performance of the plates and shells [40–46]. As for the treatment of discontinuous problem domains, extended IGA (XIGA) [47,48] can be employed. Nguyen–Thanh et al. [49] analyzed cracked Kirchhoff-Love curved shell employing XIGA.

In recent years, our research group carried out meshfree Reproducing Kernel Particle Method (RKPM) [50] buckling analyses for structural plates with curvilinear stiffeners by five DOFs flat shell formulation [51] and stiffened plates by six DOFs flat shell formulation [52]. Furthermore, buckling behavior of the cylindrical shells including circular cutouts with an efficient convected coordinate system was examined by present authors [53]. Convected coordinate system concept has been recently applied to the modeling and analysis of curvilinearly stiffened and complex shaped shells on the basis of six DOFs Mindlin–Reissner shell formulation [54]. RK meshfree formulation based on convected coordinate system with strain smoothing numerical integration techniques, i.e., stabilized conforming nodal integration (SCNI) [55,56] and sub-domain stabilized conforming nodal integration (SSCI) [57–61], is sometimes superior to conventional numerical methods so that a curvilinear geometry can be approximated effectively and shear locking can be avoided. Wang and Peng [59] proposed Hermite RK Galerkin method for the buckling analysis of thin plates employing SSCI, and superiority of the proposed method to the conventional Galerkin meshfree methods with Gauss quadrature was highlighted. Wang et al. [60] improved the previous concept for the buckling analysis of Kirchhoff-Love cylindrical shells. Wang and Wu [61] proposed nesting sub-domain gradient smoothing integration (NSGSI) based upon SSCI, and the stiffness matrix was integrated exactly for any quadratic field.

Although the present meshfree method has merits, e.g., only five DOFs flat shell model is required for analyzing 3D cracked cylindrical shell problems, the problems have not been solved yet. Tanaka et al. [62–64] effectively applied diffraction method and visibility criterion [65,66] for crack modeling in analyzing stress- and moment-intensity factors of cracked plane plate and shear deformable plate problems. So far, the modeling was adopted only for flat plate cases. We thus introduce crack modeling to the curvilinear surfaces on the basis of convected coordinates presented in [53] for analyzing cracked flat and cylindrical shell buckling problems. A singular kernel (SK) [67] is adopted for the cracked shell modeling and imposition of essential BCs. Several numerical examples for cracked flat and curved shells are presented and compared with existing solutions and FEM results. Effects of the element types are also investigated employing linear and quadratic shell elements for the FEM computations. The presence of crack to the shell structures are also discussed through the numerical results to investigate significance of defects in the structures for buckling coefficients and modes.

This paper is organized as follows. In Section 2, modeling of flat and curved shells in convected coordinates is briefly presented. We present effective meshfree modeling of cracks in Section 3. Discretization for linear buckling analysis is briefly explained in Section 4. Section 5 presents numerical examples of flat shells including cracks and circular cutouts, as well as cylinder models with cracks. Main conclusions are summarized in Section 6.

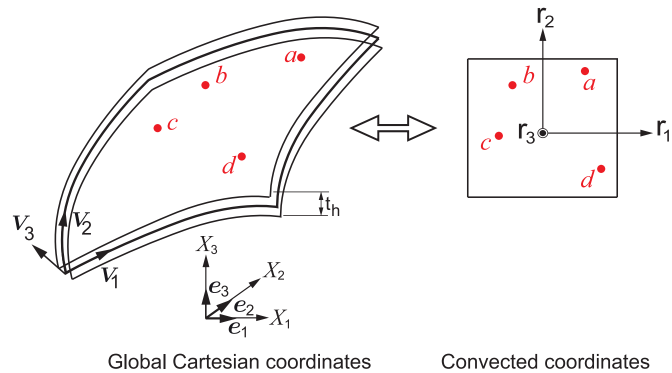

Fig. 1. A schematic illustration of coordinate transformation between global Cartesian and convected coordinates.

2. Modeling of flat and curved shells

The proposed technique is capable of transforming general 3D surface into the equivalent two-dimensional plane and vice-versa. The general shell is assumed to have a uniform thickness t_h throughout the analysis domain. A schematic illustration of the proposed mapping technique for Cartesian and convected coordinate system is shown in Fig. 1. $\boldsymbol{X} = (X_1, X_2, X_3)$ is a position vector in the global Cartesian coordinate system, while $\boldsymbol{r} = (r_1, r_2, r_3)$ stands for a position vector in convected coordinates. RKs (nodes) on mid-thickness plane can be allocated in regular or irregular pattern. The physical values between two coordinates have one-to-one correspondence, e.g., points $a - d$ in Fig. 1. The flat shell is a specific case of general curved shells.

2.1. Approximation of shell geometry and deformations

RKs are not only adopted for the curvilinear geometry interpolation, but also for the field variables approximation. The approximation scheme is same with the isoparametric FEM. The completeness condition can thus be met. Nodes can be randomly distributed on the mid-thickness plane as shown in Fig. 1 and the orthogonal unit vector $\boldsymbol{V}_i$ is defined at each node; i.e., $\boldsymbol{V}_{iI}$ for the Ith node. A position vector $\boldsymbol{X}_{\text{mid}}(r_1, r_2)$ on the mid-thickness plane (r_1–r_2 plane) of the curved shell is interpolated using the RKs as:

$$\boldsymbol{X}_{\text{mid}}(r_1, r_2) = \sum_{I=1}^{\text{NP}} \psi_I(r_1, r_2)\boldsymbol{X}_{\text{mid}I}, \tag{1}$$

where $\psi_I(r_1, r_2)$ and $\boldsymbol{X}_{\text{mid}I}$ are the RK shape function and position vector of the Ith node on the mid-thickness plane, respectively. NP is the total number of scattered nodes used for the interpolation of the mid-thickness plane of the curved shell. The RK on the