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An interface shell element for coupling non-matching quadrilateral shell meshes

Thuan Ho-Nguyen-Tan, Hyun-Gyu Kim *

Department of Mechanical & Automotive Engineering, Seoul National University of Science and Technology, 232 Gongneung-ro, Nowon-gu, Seoul 01811, South Korea

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ABSTRACT

In this study, a novel interface shell element (ISE) is developed based on a variable-node element formulation to couple non-matching quadrilateral shell meshes. Shape functions for ISEs are explicitly presented in a polynomial form with the use of appropriate supports of weight functions in moving least square (MLS) approximation. Assumed natural strains in the form of the mixed interpolation of tensorial components (MITC) approach are employed to avoid the transverse shear locking when the thickness of shell tends to zero. Moreover, an assumed membrane strain field defined over quadrilateral subdomains subdividing an ISE is used to alleviate the membrane locking in curved ISEs. Numerical experiments show the effectiveness and efficiency of ISE for connecting dissimilar quadrilateral shell meshes at a common interface.

1. Introduction

The discretization of three-dimensional surfaces into well-shaped shell elements is an important issue to obtain an accuracy in finite element (FE) analyses of shell structures. It is well known that quadrilateral shell elements are preferable to triangular shell elements because they are more accurate than triangular ones. Hence, significant efforts have been focused on developing quadrilateral mesh generation and mesh quality improvement techniques. However, poor-quality quadrilateral shell elements are generated at a transition or an interface region between two dissimilar quadrilateral meshes with different sizes and orientations when the two meshes are simply connected by ensuring the mesh conformity at the shared boundary. Hence, it is desirable to develop an efficient scheme for coupling dissimilar quadrilateral shell meshes at the transition or interface region to accommodate well-shaped quadrilateral shell meshes in each domain.

Transition elements have early presented by Bathe and Wilson [1,2] to connect finite elements of different orders. The shape functions for the transition elements can be easily constructed by modifying the bilinear interpolation of *four*-node quadrilateral (Q4) element. For non-matching meshes as shown in Fig. 1, however, the compatibility across the inter-elements cannot be satisfied, because the interpolation nodes are different on the shared edges of interfacing elements. In other words, polynomial interpolations of different sets of nodal values due to non-matching element edges at the interface do not coincide with each other. Although non-conforming elements [2–4] can be used by adding displacement constraints to satisfy the compatibility at the non-matching interface, they may lead to some limitations in FE computation [3,4].

In order to connect dissimilar quadrilateral meshes with different resolutions, interface elements [5,6] with an arbitrary number of nodes on the non-matching interface have been developed using moving least square (MLS) approximation, which is one of the effective methods to construct approximation functions in meshfree methods. Most meshfree methods [7–10] may have a difficulty in numerical integration because of misalignment of the boundaries of circular support domains and integration domains. In order to overcome the difficulty in numerical integration of MLS shape functions, the interface element method chooses the supports of the weight functions in MLS approximation to be aligned with the integration domains. Interface elements have been extended to variable-node elements with an arbitrary number of nodes on all edges of a quadrilateral element [11–14]. Shape functions for interface elements or variable-node elements satisfy the continuity at the inter-element boundaries and the completeness requirement up to the order of basis [5,6]. Recently, variable-node elements have been developed by using generic point interpolation with special bases for the numerical simulations of two-dimensional and three-dimensional cracks based on extended finite element method (XFEM) [15–17]. Variable-node elements have been applied to plate and flat shell problems [18] with

* Corresponding author.
E-mail address: khg@seoultech.ac.kr (H.-G. Kim).

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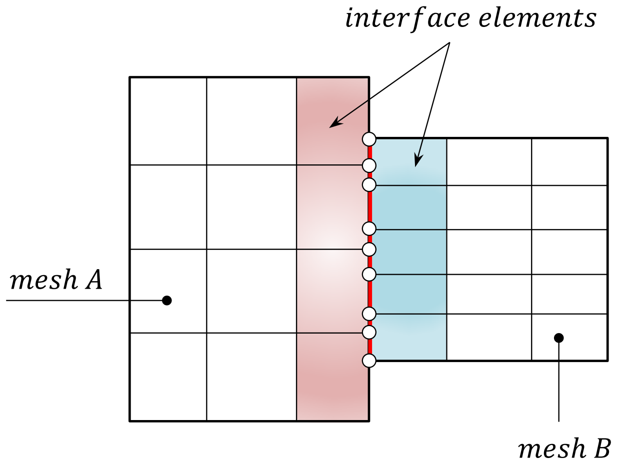

Fig. 1. The connection of a non-matching interface between dissimilar Q4 meshes by using interface elements. The interface element nodes at the non-matching interface are presented by open circles.

assumed transverse shear strains and smoothed integration methods. In the present study, we extend the variable-node formulation to an interface shell element (ISE) to couple non-matching quadrilateral shell meshes with full consideration of shear and membrane locking behaviors.

Degenerated shell elements constructed by degenerating three-dimensional continuum element, in general, perform reasonably well for moderately thick shell situations. However, they exhibit transverse shear locking phenomena when the shell thickness is very small compared to other dimensions. It means that the convergence of the element formulation in bending-dominated problems deteriorates significantly when the ratio of the shell thickness to characteristic length decreases. Many remedies have been proposed to overcome the transverse shear locking problems: selective/reduced integration method [19–21], discrete constraints enforcement method [22,23], assumed natural strain (ANS) and enhanced assumed strain (ENS) methods [24–26], reproducing kernel particle (RKP) method [27–29], and mixed interpolation of tensorial components (MITC) method [30–32]. Unlike the transverse shear locking, membrane locking occurs only when the shell geometry is curved. Some approaches have also been developed to alleviate the membrane locking: selective/reduced integration method [33,34], higher order shell elements [32,35,36] and assumed strain method [37–39]. Thus far, all methods listed above have only been developed as FE formulation that can alleviate locking problems for triangular and quadrilateral shell elements. Therefore, it is necessary to develop an efficient scheme for ISEs that can avoid transverse shear locking and membrane locking in the interface region between non-matching quadrilateral shell meshes.

In this work, an n-node quadrilateral (Qn) master element with additional nodes on the top edge is used for ISEs. Shape functions for the Qn master element are explicitly obtained in a polynomial form by properly choosing the supports of weight functions in MLS approximation. The Qn master element is divided into subdomains by projecting the additional nodes on the top edge onto the opposite bottom edge. Numerical integration of the weak form of governing equations is performed over each subdomain in which the shape functions and their derivatives are continuous within the subdomain. The present ISEs satisfy the completeness requirement so as to reproduce a linear field, and compatible shape functions are defined at the interface between non-matching Q4 shell meshes. In order to avoid transverse shear locking, MITC approach is employed by using assumed transverse shear strains based on the covariant shear strain fields at tying points along the edges of the Qn master element. Moreover, assumed membrane strains using characteristic geometry and displacement vectors [39] are employed to alleviate the membrane locking of ISEs. The present ISEs can successfully alleviate locking phenomena and show a good convergence for non-matching mesh problems. The advantage of the ISEs is that dissimilar quadrilateral shell meshes can be connected correctly without changing the meshes at the interface. Moreover, numerical results show the performance of the ISEs for coupling non-matching quadrilateral shell meshes is better than conventional approaches using a transition mesh of triangular and mixed shell elements.

In the following sections, shape functions for the Qn master element are presented based on a variable-node element formulation. Next, assumed transverse shear and membrane strains for the ISE are given in Section 3. The construction of ISEs for coupling non-matching Q4 shell meshes is described in Section 4. In Section 5, patch tests and numerical examples with non-matching shell meshes are solved to investigate the performance of the ISE. Finally, some concluding remarks are given in Section 6.

2. Shape functions for interface shell elements

Fig. 1 shows the interface elements with different numbers of nodes at the common interface between two dissimilar Q4 meshes A and B. Variable-node elements [11–14] with an arbitrary number of nodes on the edges of Q4 elements can be utilized as the interface elements to connect independently designed dissimilar meshes by giving conforming shape functions at the non-matching interface. This technique provides a useful method to satisfy the continuity and the compatibility conditions at the non-matching interface without significantly increasing the computational cost. In addition, the interface elements need to transfer rigid body motions and strain fields correctly across the interface region [5]. In this study, as shown in Fig. 2, we use a Qn master element with equally spaced additional nodes on the top edge for mapping of the interface elements to the master element in (r,s) coordinates.

Shape functions for the Qn master element can be defined using MLS approximation [11,13,40]. MLS approximation has been widely used in various methods such as meshless or meshfree methods [41–43] because it intrinsically satisfies the completeness requirement up to the order of the basis. MLS shape functions [44] can be expressed by

$$\boldsymbol{\phi}^T(r,s) = \boldsymbol{p}^T(r,s)\boldsymbol{A}^{-1}(r,s)\boldsymbol{B}(r,s) \quad (1)$$

where $\boldsymbol{p}^T(r,s) = \left[\underbrace{1, r, s, \ldots}_{m}\right]$ is the polynomial basis vector with m components in (r,s) coordinates of the Qn master element. The polynomial represented by Pascal's triangle can be chosen for the polynomial basis components to obtain a complete set of polynomial up to the order of basis. The matrices $\boldsymbol{A}(r,s)$ and $\boldsymbol{B}(r,s)$ in Eq. (1) are given as

$$\boldsymbol{A}(r,s) = \boldsymbol{P}^T\boldsymbol{W}(r,s)\boldsymbol{P} \quad (2a)$$

$$\boldsymbol{B}(r,s) = \boldsymbol{P}^T\boldsymbol{W}(r,s) \quad (2b)$$

with

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{p}^T(r^1,s^1) \\ \boldsymbol{p}^T(r^2,s^2) \\ \vdots \\ \boldsymbol{p}^T(r^n,s^n) \end{bmatrix}, \quad \boldsymbol{W}(r,s) = \begin{bmatrix} w^1(r,s) & 0 & \cdots & 0 \\ 0 & w^2(r,s) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & w^n(r,s) \end{bmatrix}$$

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