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Improved shell element for geometrically non-linear analysis of thin-walled structures

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A six-node triangular shell element was developed to study the geometrically non-linear behaviour of open-section members. The present formulation is free from shear and membrane locking due to use of mixed interpolation of tensorial components scheme. Due to model thin-walled section, an improvement is considered to update the normal vectors of elements which are located at the angle between flange and web of section. In other words, an average of director vectors is employed for these elements in updating formulation. Moreover, the total Lagrangian formulation is employed to consider large displacement and rotation. An incremental iterative technique named generalised displacement control method is utilised to solve the governing equation. Several numerical examples are studied to illustrate the accuracy and predictability of the proposed formulation.

Notation

$\mathbf{B}_{ij}$	linear strain–displacement matrix
${}_{0}C^{ijkl}$	fourth-order stress–strain tensor
e_1, e_2, e_3	unit vectors in global Cartesian system
e_{ij}^{l}	linear part of strain tensor
e_{ij}^{nl}	non-linear part of strain tensor
D	vector of nodal incremental displacements
g_i	covariant base vector of element in convected coordinate system
$h_i(\xi, \eta)$	two-dimensional interpolation function
$\mathbf{I}_3$	3 × 3 identity matrix
$\mathbf{N}_{ij}$	non-linear strain–displacement matrix
${}^{t+\Delta t}_{t}\mathbf{Q}^{i}$	rotation matrix
q	vector of incremental nodal displacements
${}^{t}_{0}S^{ij}$	second Piola–Kirchhoff stress tensor
t	time
t_i	thickness of node i
u	nodal displacement vector in global Cartesian system
u, v, w	nodal displacements
u_l	linear part of nodal displacement
u_q	quadratic part of nodal displacement
V_1^{i}, V_2^{i}	unit vectors orthogonal to V_n^{i} and to each other
V_n^{i}	director vector of node i
x_i	position vector of node i
α_i, β_i	rotation of V_n^{i} about V_1^{i}, V_2^{i}
ε_{ij}	Green–Lagrange strain tensor
${}^{t+\Delta t}_{t}\Theta^{i}$	skew-symmetric matrix
ξ, η, ζ	convected coordinates

1. Introduction

Thin-walled structures can be divided into beams, plates and shells. Thin-walled structures are now widely used due to their low weight, high flexural capacity and easy fabrication. One of the most common structural elements is the open-section beam and analysis of the non-linear behaviour of these members is thus necessary. These structures can be modelled in two ways. One of them is to use beam theories to convert three-dimensional (3D) behaviour into 1D elements. The other way is to model the beam using 2D shell elements based on the finite-element (FE) method.

It is essential to have an efficient method for analysing shell structures simply and accurately. Some procedures have been developed to employ 2D shell elements in geometrically non-linear analysis due to their simple formulation. Degenerated shell element theory was first developed by Ahmad *et al.* (1970) for analysing curved shell elements and details of the general developments of degenerated shell element methods have been reported by Bathe (1982), Crisfield (1986) and Chapelle and Bathe (2011). Predicting the geometrically non-linear behaviour of shells has been proven to be challenging. To achieve this goal, the large displacement and rotation of the shells in conjunction with the small-strain assumption have to be considered. Many technical papers have been published on this subject, among which are the remarkable works of Hughes and Liu (1981), Dvorkin and Bathe (1984) and Gal and Levy (2006).

An attractive approach to the formulation of shell elements is the mixed interpolation of tensorial components (MITC) method. Dvorkin and Bathe (1984) proposed a four-node general shell element, called MITC4. Later, the same researchers presented an eight-node quadrilateral element using the MITC approach and showed the capability of this formulation in linear and non-linear analyses of shell/plate structures (Bathe and Dvorkin, 1986). The applications of shell elements developed based on the MITC method for linear and

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Julia Schneider

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