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An element subscale refinement for representation of the progressive fracture based on the phantom node approach

S. Mostofizadeh [a,b,c,*], F.P. van der Meer [a], M. Fagerström [b], L.J. Sluys [a], R. Larsson [b]

[a] Department of Structural Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
[b] Division of Material and Computational Mechanics, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden
[c] Materials Innovation Institute (M2i), Delft, The Netherlands

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ABSTRACT

A new approach for the analysis of the ductile fracture of thin-walled large scale structures is developed. The method proposes a subscale refinement of the elements containing the crack. It allows for smooth progression of the crack without furnishing required level of the mesh refinement, and a more detailed representation of the crack tip and crack kink within the cracked elements. This approach is based on the phantom node method and is intended to be applicable for different types of elements including both low and high order elements. Numerical examples for dynamic crack propagation are presented and compared to conventional solutions to prove the accuracy and effectiveness of the proposed approach.

1. Introduction

Thin-walled structures are widely used for different applications, such as maritime structures, off-shore structures, and aircraft fuselages. These various engineering applications call for a reliable methodology to predict their failure under different loading conditions. One of the main challenges of such a problem is to find a methodology to analyse the ductile failure of large-structures using shell theory. In this respect a complexity addressed in the current paper is accounting for the fine scale of ductile failure.

Analysing large-scale thin-walled structures requires sufficient level of mesh refinement to maintain a high degree of accuracy in the results. However, mesh refinement inherently adds to the cost of the computation. Therefore, there is a need for a methodology that simplifies such analyses, and yet includes the required level of detail in the model. In line with developments by Rabczuk et al. [1] and Mostofizadeh et al. [2], we propose herein a method to ensure smoothness and accuracy of the crack propagation without requiring a high degree of mesh refinement. A new crack tip element based on the phantom node method [3] is presented which brings in the possibility to represent the growth of a crack through a single element in multiple steps using a subscale refinement. The current approach bears similarity to the developments by Zi and Belytschko [4], Chau-Dinh et al. [5] and Xiao and Karihaloo [6]. However, in the current method the treatment of the crack kinks internal to the element can also be represented which is an addition to the previous developments. The method is applicable to different type of elements with both low and high order approximations and it does not require any change in the spatial discretisation of the neighbouring elements which leads to less degree of mesh refinement.

The paper is outlined as follows. In Section 2, the subscale refinement of a crack tip element based on the phantom node method is described. In Section 3, the formulation is extended to shell theory. In Section 4, the continuum material model and interface material model are summarised. In Section 5, numerical results are verified and compared with the results obtained from the conventional phantom node method. Finally, the paper is concluded in Section 6, where conclusions are discussed.

2. Subscale refinement of displacement field

In this section, the subscale refinement of the crack tip element based on the phantom node method will be presented. The underlying concept of this method is to enhance the representation of the kinematics of the discontinuity with a subscale refinement. That is, additional degrees of freedom are added on the subscale level of the cracked element. The conformity of this additional field

* Corresponding author at: Department of Structural Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands.

E-mail address: salar.mostofizadeh@chalmers.se (S. Mostofizadeh).

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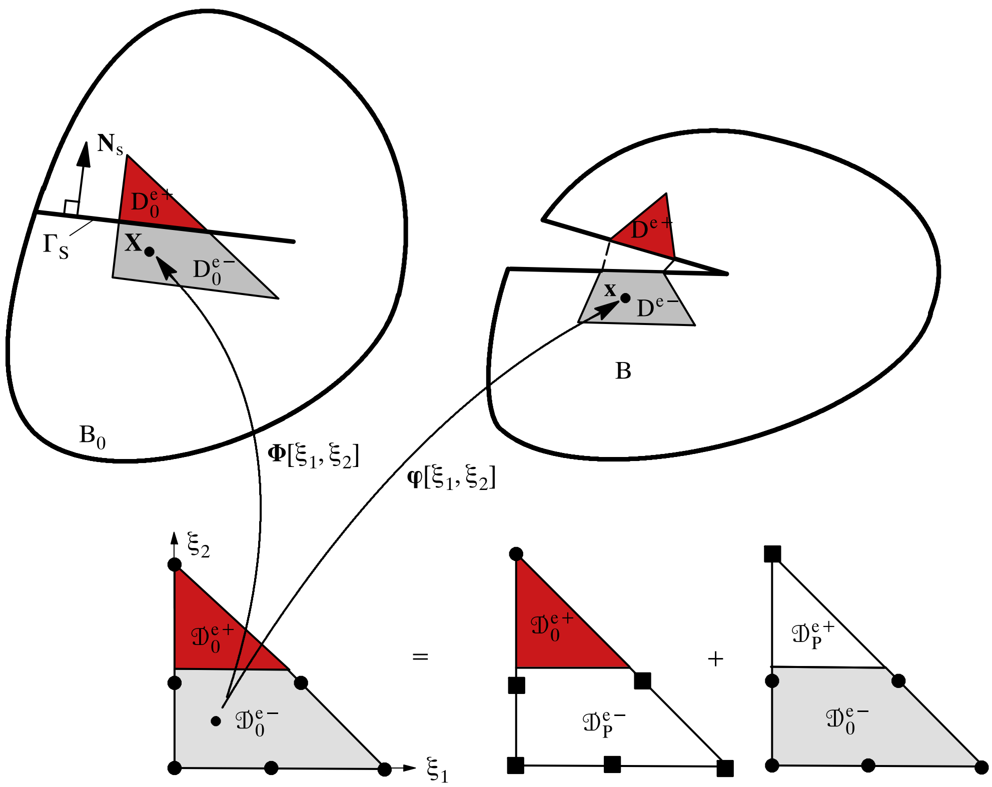

Fig. 1. A domain containing a crack in which the displacement jump is described by the phantom node method - the solid circles represent real nodes and the solid squares represent phantom nodes.

is imposed with Dirichlet boundary condition on the boundary nodes of the subscale problem.

Below, a review of the phantom node method will be given, followed by the details of the subscale refinement of the crack tip element. It should be emphasised that we herein consider standard Phantom node kinematical relations for a 2D continuum with cracks, although presented in a somewhat non-standard format to provide a basis for the subsequent application to shell problems in Section 3.

2.1. A review on the phantom node method

To set the stage, we introduce three configurations: the reference (or inertial) cartesian configuration $\mathscr{B}$, the undeformed (material) configuration B_0 and the deformed (spatial) configuration B as indicated in Fig. 1. In this framework, any material point (in 2D) $\mathbf{X} = (X_1, X_2)$ in the undeformed configuration is related to a point in the intertial configuration $\xi = (\xi_1, \xi_2)$ via the mapping

$$\mathbf{X} = \boldsymbol{\Phi}[\xi]. \tag{1}$$

Similarly, any point $\mathbf{x} = (x_1, x_2)$ in the deformed configuration relates to the point ξ in the inertial configuration via the (time-dependent) mapping from the inertial to the deformed configuration, herein denoted as the placement, as

$$\mathbf{x} = \boldsymbol{\varphi}[\xi, t]. \tag{2}$$

Analysing problems that concern strong and weak discontinuities, such as cracks, and shear bands, poses a modelling challenge. In the conventional finite element method, accuracy of the approximation field is maintained provided that the field of approximation is sufficiently smooth and continuous. In case of presence of a crack within an element, the displacement field is continuous on each side of the crack, while it is discontinuous across it. Exploiting the partition of unity concept, cf. Melenk and Babuška [7], this has been treated in the eXtended Finite Element Method (XFEM), pioneered by Belytschko and Black [8] and Moës et al. [9], by enriching the approximation function with additional bases allowing for the representation of discontinuities. However, depending on the enrichment function employed, neighbouring elements may require changes to be made.

An alternative approach, the phantom node method, has been proposed by Hansbo and Hansbo [3]. In terms of the represented kinematics, the phantom node method is identical to XFEM [10], but it enjoys an easier implementation. In the current approach, rather than adding additional degrees of freedom as in XFEM, a jump in the displacement field is realised with overlapping elements as indicated in the bottom of Fig. 1. Each of these elements, whose support is partially active, represents the displacement field on one side of the crack. It requires the integrations to be carried out only partially, on the active support of the overlapping elements.

Now, consider a discretised cracked body as in Fig. 1, and particularly a subdomain (equal to an element) cut by the crack. In the material configuration, this subdomain (element), denoted D_0^e, is decomposed into a plus side, D_0^{e+}, and a minus side, D_0^{e-}, on either side of the discontinuity surface, Γ_S with normal $\mathbf{N}_S$. As for the mapping $\boldsymbol{\Phi}$, it can then be approximated in a standard isoparametric[1] fashion, irrespectively if it is cut by a crack or not, as

$$\boldsymbol{\Phi}^{h,e} = \sum_{i \in I} N^i[\xi_1, \xi_2] \hat{\mathbf{X}}^i \tag{3}$$

[1] To make it clear: even though we in the continuous case consider three different configurations and a unique one-to-one mapping between a point ξ in the inertial configuration and a point $\mathbf{X}$ in the undeformed configuration, we consider for simpler implementation of the discretised case a single parent element (with local coordinates) in the inertial configuration.