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Analysis of strain gradient Reissner–Mindlin plates using a C^0 four-node quadrilateral element

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Abstract

The weak form of Reissner–Mindlin plate model in the context of the classical continuum theory requires C^0-continuity of the lateral deflection as well as rotation fields. However, due to the presence of higher-order derivatives, the same plate model based on strain gradient elasticity demands C^1-continuity of interpolation functions for a standard finite element (FE) formulation. On the other hand, it is known that C^0 interpolation functions result in more stable and cost-effective elements. Accordingly, a four-node quadrilateral gradient-enhanced plate element using C^0 interpolation of the field variables is introduced. The main idea is to start with an eight-node quadrilateral element on which any field variable and its spatial derivatives are independently interpolated via standard C^0 shape functions. By introducing appropriate algebraic constraints, the degrees of freedom corresponding to the midside nodes of the eight-node element are then eliminated and a quadrilateral element with four nodes on its corners is constructed. Accuracy and performance of the proposed element in several examples and for a wide range of parameters is investigated. It is shown that the new element can successfully capture the size-dependent behaviour of plates at small scales, has a proper rank (contains no spurious zero-energy modes), passes the patch test for thin as well as thick plates in an arbitrary mesh, and is free of shear locking. Furthermore, the introduced element can reproduce the results of the Reissner–Mindlin plate model based on the classical continuum theory when the plate thickness is far greater than the material length scale parameter.

Keywords: Reissner–Mindlin plate, Strain gradient elasticity, C^0-continuity

1. Introduction

Various experimental observations demonstrate that behaviour of structures at micron scale is size-dependent [1–3], and a general conclusion is that smaller is stronger [4]. These scale effects are due to the fact that the size of the microscopic material constituents of such structures cannot be considered to be small compared to the overall dimensions of the structure itself [5].

Due to lacking intrinsic length scales, experimental observations at micron scale cannot be captured by the classical continuum theory. However, the strain gradient continuum theory has been proven to be able to model the size dependent elastic and plastic behaviour of materials at micron scales (see, for example, Refs. [1, 2, 6]). The foundations of strain gradient elasticity theory were laid down in the 1960s through the pioneering works of Mindlin [7–9] and Toupin [10, 11]. The first strain gradient elasticity theory, employed in the present study, is a special case of the theory of elasticity with microstructure elaborated by Mindlin [7]. Aifantis [12] proposed a simple version of Mindlin's theory that uses the so-called Lamé moduli besides an additional material length scale as the constitutive parameters. The

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