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Junctions in shell structures: A review

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ABSTRACT

Many shell structures used in modern technology consist of regular shell parts joined together along their common boundaries. We review different theoretical, numerical, and experimental approaches to modelling, analyses and design of the compound shell structures with junctions. Several alternative forms of boundary, continuity and jump conditions at the singular midsurface curves modelling the shell junction are reviewed. We also analyse the results obtained for special shell structures containing the cylinder–cylinder intersections, cone– , sphere– , and plate–cylinder junctions, tubular joints as well as other special types of junctions appearing in complex multi-shell structures.

Contents

1. Introduction

Many complex shell structures used in modern technology consist of regular shell parts joined together along their common boundaries. Automobile bodies, aircraft fuselages, water and oil tanks, silos, branching and intersecting pipelines, pressure vessels with nozzles etc. are just a few typical examples of such thin-walled constructions. Even supposedly regular shell parts may contain stiffeners, stepwise thickness changes, parts made of different materials or reinforced in different directions etc., which may cause some kinematic and/or dynamic fields of the boundary value problem to be discontinuous at specific curves or points on the shell base surface. Some shell junctions may have their own mechanical properties allowing the adjacent shell elements to deform (usually rotate) one with respect to another, or such deformability develops at some level of deformation, as in the case of

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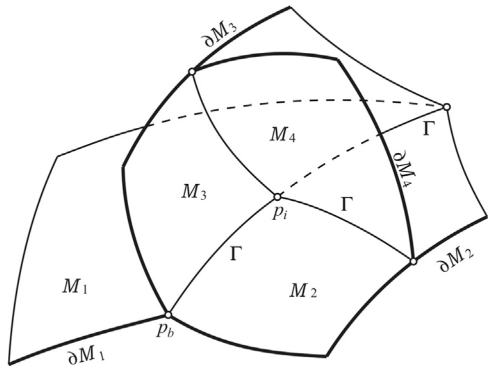

Fig. 1. Irregular piecewise smooth shell base surface composed of regular surfaces M_n joined along singular curves Γ.

phase transition or plastic hinge of the shell material.

It was recognized long ago that in order to analyse the compound shell structures it is necessary to complete the BVP of the regular shell structure with additional relations – the continuity conditions – by adjusting the boundary conditions along the joined parts of regular shell elements. The form of these conditions depends on the shell model used in the analysis. In most discussions the compound irregular shell structure is divided into regular parts each having a smooth and regular surface as its base surface. The regular shell parts are modelled separately, and all the parts are then assembled into the whole structure by adjusting boundary conditions of the adjacent shell elements along the junctions, with possible account of additional different mechanical properties of the junction itself.

In the approach proposed by Makowski et al. [1,2] within the non-linear theory of thin elastic shells, the whole compound shell structure was modelled by a material surface-like continuum capable of resisting to stretching and bending, Fig. 1. From the Principle of Virtual Work written for the whole shell structure several forms of static and kinematic jump conditions at the junctions were formulated, besides the equilibrium equations and static boundary conditions known from the theory of thin regular shells.

Within the resultant six-field non-linear shell theory, a refined approach was used by Chróścielewski et al. [3,4]. Geometry of the undeformed irregular shell structure was described by a union of piecewise smooth surfaces and curves. The curves with their intersections formed a complex reference network. Each curve in the network may represent a stationary singular surface curve modelling the fold, junction, intersection etc., but also a one-dimensional continuum endowed with its own dynamic, kinematic, and/or material properties. Then an integral identity with meaning of the Principle of Virtual Work allowed one to formulate the equilibrium equations, dynamic boundary conditions and unique definitions of the surface strain measures known from the six-parameter model of the regular shell parts. Additionally, one obtained the appropriate jump conditions at the shell junctions. Konopińska and Pietraszkiewicz [5,6] formulated the exact, resultant dynamic jump conditions for the branching (see Fig. 2) and intersecting shells, with the unique work-conjugate kinematics at the singular curves constructed in Konopińska and Pietraszkiewicz [7] and Pietraszkiewicz and Konopińska [8] (see Figs. 3 and 4). The most general jump conditions for the surface mass, linear momentum, angular momentum, energy and entropy at the moving singular surface curves have recently been formulated by Pietraszkiewicz and Konopińska [9] within the refined resultant thermodynamics of shells worked out by Pietraszkiewicz [10].

Development of the numerical finite element method (FEM) considerably changed modelling and analysis of complex shell structures with junctions. In the direct numerical approach the continuity (or jump) conditions are supposed to be automatically satisfied in the process of assembling the global stiffness matrix from local matrices of individual finite elements. One should note, however, that accuracy of such numerical satisfaction of continuity at the junction depends on the type of finite elements used in the numerical simulations. Any all-purpose computer FEM code offers many types of membrane, plate, shell and 3D finite elements of different complexity and accuracy. It is not apparent in advance which of the FEs available is suited best for assuring the most complete continuity of the analysed compound shell structure. Thus, in many recent design cases of responsible shell structures with junctions, different methods of analyses – analytical, numerical, and/or experimental – are still used independently and parallely, and the results are compared in order to achieve the best security of structural design.

In this paper we review some achievements on modelling and analysis of shell structures composed of regular shell parts joined together along the common boundaries. In Section 2 we recall some books and review papers in which also some compound shell structures with junctions were discussed. Then in Section 3 we analyse the results on various forms of boundary, continuity, and jump conditions between regular parts of the shell structure for general geometries of their base surfaces. Finally, in Sections 4–9 we summarize the published literature on analysis of special shell structures containing the cylinder–cylinder intersections, cone–, sphere–, and plate–cylinder junctions, compound shells of revolution, tubular joints as well as other special types of multi-shells commonly used in modern technology. In most cases the results obtained in each of the referred paper are characterised in descriptive concise way, which should help the reader to gain

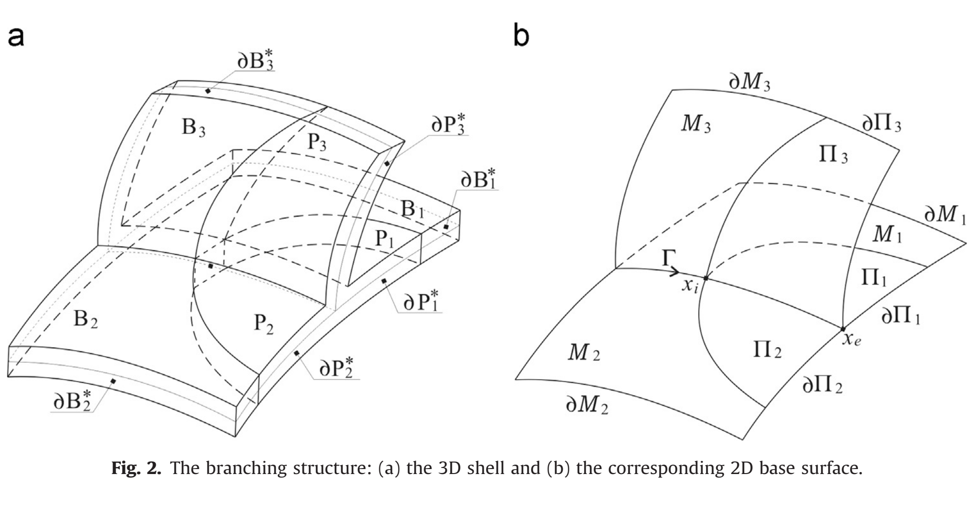

Fig. 2. The branching structure: (a) the 3D shell and (b) the corresponding 2D base surface.