DOI: 10.5075/epfl-ICSS12-2018-44-46

1D COUPLING ELEMENT FOR EFFECTIVE MODELLING OF SANDWICH PANELS

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1. INTRODUCTION

The considerably superior specific strength and stiffness of sandwich panels in relation to conventional structural components makes their employment for deck systems and two-way spanning structural applications a highly attractive alternative. An accurate description of the mechanical response and encountered failure modes in a sandwich panel deck system requires high-fidelity detailed finite element models, capable of capturing geometric and material nonlinearity both globally and locally. In this context, besides the detailed modelling of the panel geometric domain, the accurate representation of compatibility between deformable deck components, such as along weld lines, is essential for the local response evaluation. Considering all-steel sandwich decks, the welded connection between the panel core and faces, the edgewise connection of adjacent panels, as well as the connection of the panel deck with the underlying grillage of supporting beams and the load patches transferring the equipment loading to the panel top surface require a sophisticated modelling approach.

When modelling connected deformable components, the geometric complexity of the system often imposes severe constraints on the meshing of the respective interfaces to achieve coupling, such as the requirement for nodal alignment, compliance of element shapes and density, proportionality of element sizes and the implementation of geometrically complex transitional meshes. This paper presents an efficient and highly accurate computational strategy for coupling shell surfaces modelled with non-matched Finite Element (FE) meshes along a line interface of arbitrary spatial orientation. The developed formulation allows independent meshing of the coupled domains, enabling a more efficient discretisation procedure to be achieved and overcoming the previously noted modelling shortcomings. It is therefore particularly applicable in the modelling of deformable components which are independently meshed and coupled along a weld line, as well as in the case of partitioned models with a different level of discretisation detail in each child partition, dictated by the geometry, applied loading and the specific boundary conditions.

2. 1D LINE COUPLING ELEMENT FORMULATION

The coupling constraint is introduced along the line interface in the weak form of the global boundary value problem, by using a two-field Lagrangian functional which represents the contribution of the tied interface to the total potential energy of the system. An element-to-element coupling is introduced along the intersections of the tied interface with the faces of a different subset of active elements for each independently discretised domain. This mesh-tying formulation has been implemented in the form of a coupling element which consists of two arbitrary 2D solid FE faces, located at opposite sides of the 1D line interface. The constraint over the tied interface is enforced by employing the augmented Lagrangian multiplier formulation, where the total potential energy contribution of the element to the system includes a second-order penalty regularisation [1]:

$$\Pi_{\boldsymbol{ALM}} = \int_{\Gamma_c} \left[\boldsymbol{\lambda} \cdot \mathbf{g}(\mathbf{u}) + \frac{1}{2} \cdot \varepsilon \cdot \mathbf{g}(\mathbf{u}) \cdot \mathbf{g}(\mathbf{u}) \right] \mathrm{d}\Gamma_{\boldsymbol{c}} \tag{1}$$

In the above expression, $\boldsymbol{\lambda}$ is an independent variable field of Lagrangian multipliers introduced along the coupled interface $\{\Gamma_c\}$, $\mathbf{u} = \{\mathbf{u}^1, \mathbf{u}^2\}$ is the domain displacement field, $g(\mathbf{u}) = \mathbf{u}^1 - \mathbf{u}^2$ is the gap vector field, and $\varepsilon \geq 0$ is a penalty parameter. The coupling interface contributions to the first order variations of the total potential energy in Eq. 1 with respect to $\mathbf{u}$ and $\boldsymbol{\lambda}$, which relate to resistance forces and constraint equations respectively, are obtained as**:**

$$\delta\Pi_{\boldsymbol{ALM}}^{\boldsymbol{u}} = \int_{\boldsymbol{\Gamma_c}} [\boldsymbol{\lambda} + \varepsilon \cdot \mathbf{g}(\mathbf{u})] \cdot \frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{u}} \cdot \delta \mathbf{u} \;\, \mathrm{d}\Gamma_{\boldsymbol{c}} \tag{2}$$

$$\delta\Pi_{ALM}^{\lambda} = \int_{\boldsymbol{\Gamma_c}} \delta\boldsymbol{\lambda} \cdot \mathbf{g}(\mathbf{u}) \;\, \mathrm{d}\boldsymbol{\Gamma_c} = \mathbf{0} \tag{3}$$

The expressions of the element stiffness matrix and resistance force vector are obtained by expressing the Lagrangian multiplier and displacement fields in a discrete form. This is achieved by means of interpolating the values obtained at *a priori* defined collocation points and nodal locations, using Lagrangian polynomial shape functions. The concept is illustrated in Fig. 1(a), where two independently discretised regions $\{{\Gamma_h}^{(i)}\}$, i=1,2, are coupled along the 1D interface $\{\Gamma_c\}$. The active subset of elements in each mesh are denoted as $\{{\Gamma_{c,h}}^{(i)}\}$.

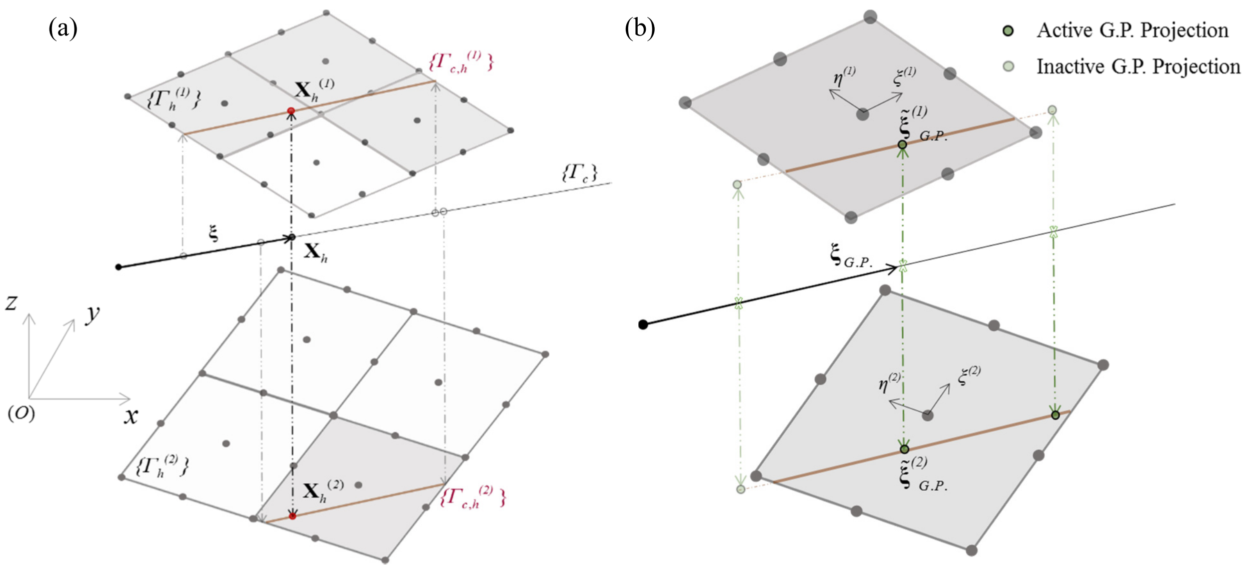

Fig. 1: (a) 1-D coupling element consisting of two 9-noded shell finite elements faces, (b) Gauss Point projection procedure for numerical integration of the stiffness matrix.

For the numerical integration of the stiffness matrix along the interface Gaussian quadrature is employed. The interface is sub-divided into a finite number of regions where Gauss points are defined and are subsequently projected on the element faces. The component matrices are evaluated at the Gauss point projections, $\xi^{(i)}_{G.P}$, expressed in the respective natural coordinate system of the two elements on the coupled surfaces, as illustrated in Fig. 1(b).

3. NUMERICAL EXAMPLES

The effectiveness and accuracy of the proposed coupling element formulation are illustrated using detailed models at critical regions of an all-steel sandwich panel deck system, where a thorough investigation of the connection between discrete plated components is required, as illustrated in Fig. 2. The sandwich panels comprise a rectangular honeycomb core configuration, consisting of a grid of 3 mm thick rectangular steel strips, laser-welded to the top plates, also of 3 mm thickness. The panel compartments, underlying beams and loading patch plates used as equipment supports have been discretised using 9-noded co-rotational curved shell nonlinear elements [2] in accordance with a high-fidelity modelling strategy for metal sandwich panels [3]. The deformed shapes, contour plots and graphs have been obtained using ADAPTIC [4], in which the coupling element has been implemented.

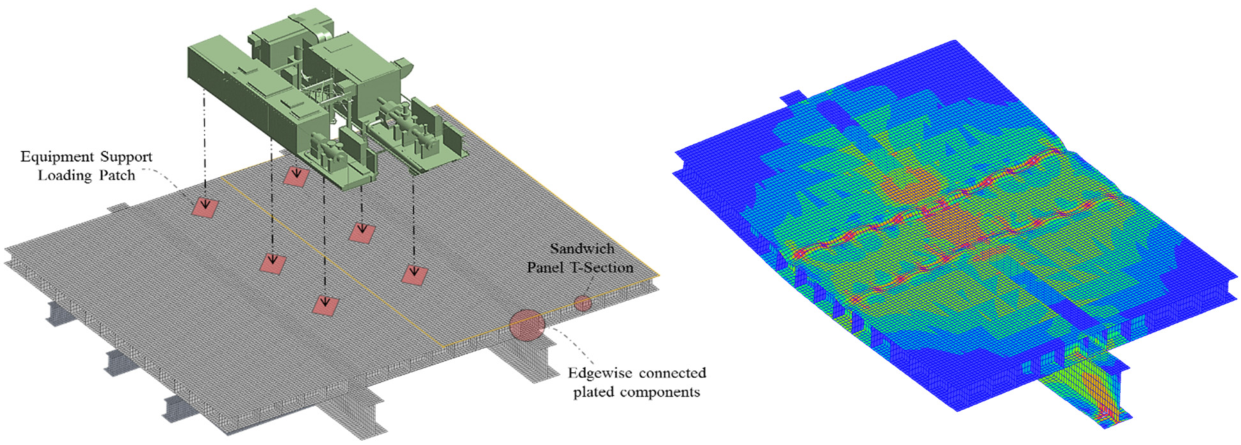

Fig.2: High-fidelity modelling of all-steel sandwich panel deck system and identification of critical contact regions.

Fig. 3(a) illustrates the element application in modelling the coupling of non-matching meshes in locations of different plated component edgewise contact. The contour plot highlights the ability of the element to effectively transfer a planar stress field between the two non-matched meshes in contact. An independent meshing of adjacent sandwich panel domains is thereby allowed without necessitating the implementation of complex transitional mesh regions. Fig. 3(b) illustrates the element application in modelling the coupling of sandwich panel plates and core strips for an arbitrary orientation of the weld line, where clearly the intersection of the line interface with the element edges of the top plate are non-coincident with nodal locations over the core strip. This enables the independent meshing of the various panel compartments, with a higher level of discretisation detail being employed in regions characterised by high stress variation and potential instability. Lastly, Fig.3(c) illustrates the element application in coupling independently meshed shell surfaces along a line interface. A load patch skewed by 45° in the x-y plane underneath an equipment support is coupled to the top panel plate along four weld lines on the patch perimeter. The use of the coupling element allows a significantly reduced mesh density (left), as compared to the case where a fine compliant mesh is required for the application of conventional node-to-node coupling or continuous meshing at coincident nodal locations. Evidently, the response obtained at the patch centre with the use of the proposed coupling element is comparable to that obtained using conventional translational joint elements for nodal coupling. The presented examples clearly illustrate the numerous modelling benefits associated with the employment of the proposed formulation, in addition to its accuracy and effectiveness. Beyond leading to a simple and effective discretisation procedure, the proposed approach leads to a more efficient use of computing time and resources.

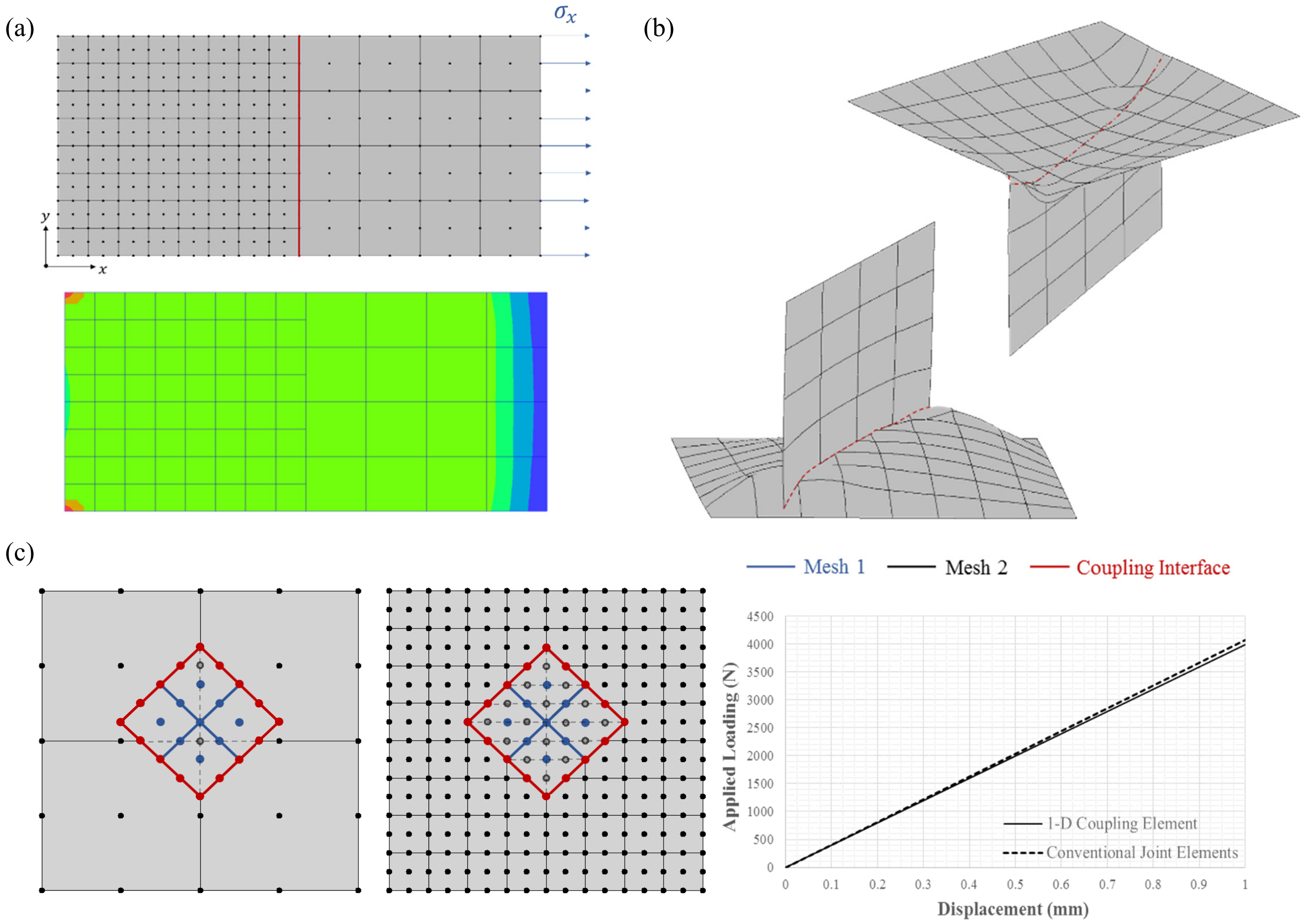

Fig.3: Applications of the 1D coupling element in modelling of contact problems with non-matching meshes: (a) Edgewise plate contact, (b) weld line modelling in rectangular honeycomb sandwich panel plate and core strip T-sections, (c)weld line modelling in load patch – sandwich panel plate contact regions.

4. CONCLUSIONS

This paper presents a novel formulation for translational coupling of two surfaces discretised with non-matching shell element meshes along a line interface with any spatial orientation, which has particular applications in the modelling of sandwich systems. The formulation is developed as a coupling element consisting of two arbitrary 2D element faces on either side of the interface, where the overall interface is discretised into several coupling elements. It is therefore particularly applicable in the modelling of independently discretised components that are welded and to partitioned models with different levels of discretisation detail in each child partition. The presented approach addresses major shortcomings in conventional coupling of surfaces along a line, thus achieving significant modelling benefits.

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