A componet based bounded sub-structuring approach for large geometrical deformations in slender structures

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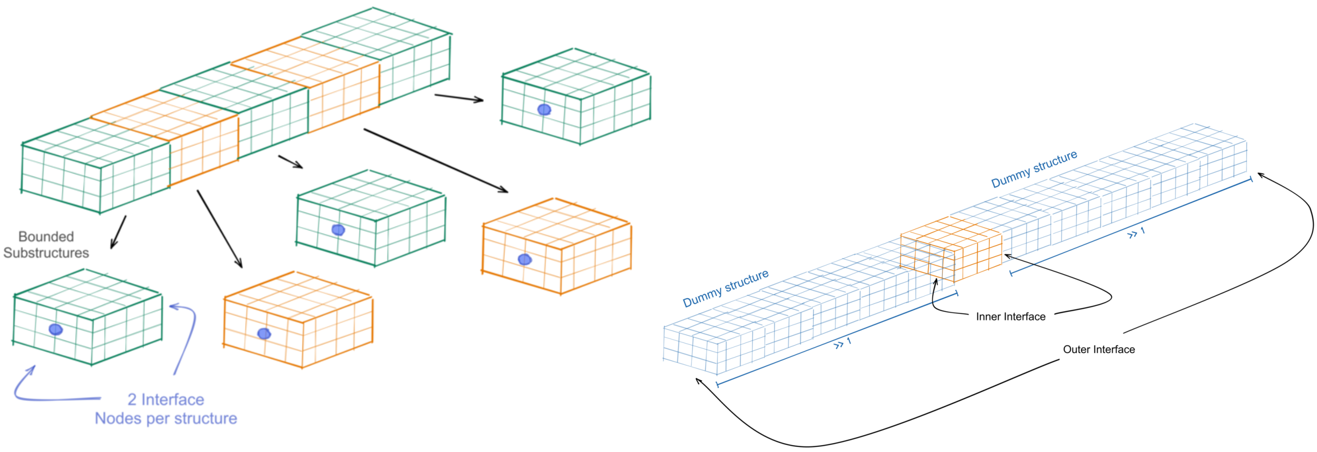
EXTENDED ABSTRACT

1 Introduction

To include a finite element structures into a multibody system the classic approach is to utilize the floating frame of reference formulation together with a **single** linear flexible body. Where the flexible body is generated by a component mode synthesis (CMS) either following a Craig Bampton or a Craig Chang reduction [1]. By doing this we linearize and thus, material as well as geometrical nonlinear effects due to large deformations inside the flexible body are not covered. Also dependent on the loading the floating frame of reference may rotate and thus boundary conditions in the system can differ from the actual finite element reference model. These issues have also been pointed out by Shabana [2] who concludes that the generality of linear flexible bodies is severely limited up to a point where boundary conditions on the final structure need to be considered before reduction and thus the generality of a reduced model is limited. He also argues that the flex body approach with floating frames of reference in itself should be treated with extreme care when used in commercial software.

Our approach is to subdivide a finite element structure into multiple bounded sub-structures, and to reduce each sub-structure individually. This will allow for geometrical nonlinear deformations at least in a global sense. Of crucial importance here is the interface between each of the bounded sub-structure elements, i.e. how the sub-structures interact or connect with each other. In a conventional method the interface would be either rigidified using an RBE2 (i.e. all nodes of an interface move together w.r.t. one master node) or RBE3 (i.e. forces to a master node will be distributed as a weighted sum to the interface nodes and vice versa) element. Which either result in a much to stiff or much to soft interface. Especially when following a sub-structuring approach this is not acceptable due to the accumulation of error from each element. We instead construct the reduced sub-structure by asking how would the interface deform if it would **not** be on the boundary of a larger structure but in the middle.

2 Method



(a) (b)

Figure 1: (a) Initial sub-structuring (b) Sub-structure extended by dummy structure

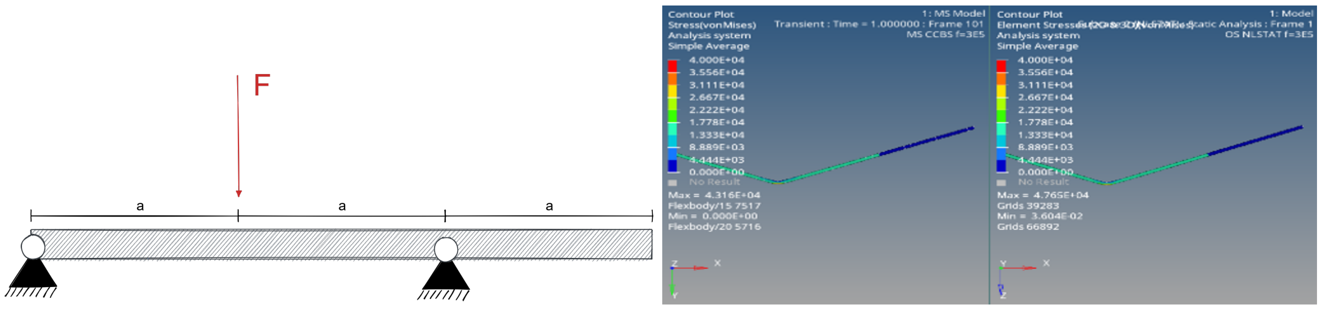
Even for a slender structures we start with an arbitrarily detailed 3D finite element model $\mathscr{F}$. We slice the model into sub-structures $\mathscr{S}_i$ s.t. $\mathscr{F} = \Uplus_{i=1...n}\mathscr{S}_i$ like seen in Figure 1a. For brevity we focus on the case where all sub-structures $\mathscr{S}_i$ are similar to each other ($\mathscr{S} = \mathscr{S}_i \quad \forall i = 1\ldots n$), in general this isn't necessary, if it is the case the presented reduction needs only to be done exactly once and the reduced sub-structure can be used for any instance where it occurs. Each sub-strucure $\mathscr{S}$ is constructed such that it has exactly two interface nodes I_1, I_2, one on the left and one on the right end. $\mathscr{S}$ will be reduced to a total of $n_{\text{dof}} = 12$ degrees of freedom, for which six will be rigid body modes and six are bending modes, i.e. we end up with exactly one mode for each degree of freedom. Each piece can thus be kinematically determined just by specifying the two interface node locations and orientations, since the method yields no internal degrees of freedom this also reduces the number of independent coordinates during simulation. Also note that the stiffness matrix of the elements can be diagonalized as the modes are linearly independent and thus can be chosen orthogonal.

How to construct the bending modes is of crucial importance and our main contribution. As already discussed we want to capture a realistic deformation of the boundary surface to assure the correct transfer of interface forces. Our approach to do this is by construction of a dummy structure $\mathscr{D}$ in which's center the sub-structure $\mathscr{S}$ is embedded like seen in Figure 1b. The interface nodes I_1, I_2 and corresponding constraints are removed during this step. $\mathscr{D}$ and $\mathscr{S}$ share the same material properties and $\mathscr{D}$ is constructed s.t. it's nodes on the interface surface match those nodes of $\mathscr{S}$ exactly. Each interface node on the surface is tied at the individual nodes n_i of the interface, to connect to $\mathscr{D}$. It is important to note that due to this construction each node n_i is only constrained by the material stiffness and besides this free to move. Deformations at the very left or right end outer interfaces O_1 and O_2 of the dummy structure transfer to the sub-structure interface surface, where the inner interfaces I_1, I_2 would be, while the influence of the actual constraints of the outer interface surface, e.g. how those are constrained together diminishes with the distance from the inner interface surfaces.

To obtain the modes we rigidify each end of the outer interface O_1, O_2 and perform a modal reduction with the outer interface nodes selected as independent nodes to the CMS method and reduce hereby to a total of 12 modes m_k, $k = 1 \dots 12$. For each of these modes m_k and at each node n_i of the interface surface (between dummy and sub-structure) we measure how much force f_i^k is transferred from the dummy structure to the actual sub-structure. Using these interface forces f_i^k we can calculate the deformation u_i^k of the standalone sub-structure under a static load case and use those deformations u_i^k as the modal basis $m_k^* = 1 \dots 12$ for our method. Notice that we don't add an actual extra constraint to the interface surface nodes but instead rely on the linear subspace spanned by the modal basis m_k^*.

The advantage of this approach is that there is no extra stiffness introduced. The price we pay for this is that the interface constraints cannot be perfectly satisfied under extreme loads.

3 Results



(a) (b)

Figure 2: (a) Benchmark setup (b) Comparison MBS + our approach vs. nonlinear FE

We apply our method to the benchmark model suggested in [2] as depicted by Figure 2a while using a substantially larger actuation force, to yield an even larger nonlinear effect. The result comparison between the sub-structured flex body using 12 identical sub-structure elements (having 12 degrees of freedom each) inside the multibody simulation and the full 3D nonlinear finite element model using 68,000 elements shows a very good correlation in displacements and element stress as seen in Figure 2b (Reference results on the right, reduced model results on the left, color depicts element stress). The transient MBD simulation took only 0.17s while the nonlinear static finite element model solved in 968s. Results for the linear model using the standard floating frame of reference and only one classic flexible body don't correlate very well.

We also show how the exact same sub-structure element performs in different models and under different loading conditions, and compare to simpler rigidified connections using classic interface constraints such as RBE2 and RBE3.

4 Conclusion

Our results closely match the finite element reference while using substantially less degrees of freedom, also it simulates much faster. We conclude thus that linear flexible bodies using bounded sub-structering can at least for slender structures be general and work even in the case of large deformations.

Even though we demonstrated the method only for slender structures we believe that the idea is more general and we give an outlook on how it can be extended to other non slender sub-structures.

References

[1] R. Craig and A. Kurdila. Fundamentals of Structural Dynamics, 2nd Edition, Willey, 2006.

[2] A. Shabana and G. Wang. Durability Analysis and Implementation of the floating frame of reference formulation. J Multibody Dynamics, 232(3): 295-313, 2018.