Mortar Contact for Implicit Analysis

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1 Introduction

The Mortar contact in LS-DYNA[1,2] was originally implemented as a forming contact intended for stamping analysis[3] but has since then evolved to become a general purpose contact algorithm for implicit time integration. The Mortar option is today available for automatic single- and surface-to-surface contacts with proper edge treatment, and optional features include tie, tiebreak and interference. The Mortar contact is a penalty based segment-to-segment contact with finite element consistent coupling between the non-matching discretization of the two sliding surfaces and the implementation is based on [4,5]. This consistency, together with a differentiable penalty function for penetrating and sliding segments, assert the continuity and (relative) smoothness in contact forces that is appealing when running implicit analyses. The algorithm is primarily focusing on accuracy and robustness, and the involved calculations associated with this aim make it expensive enough to not be recommended for explicit time integration except for those cases where other algorithms for some reason are inadequate. While the Mortar contact is not to be seen as superior for all implicit contact situations, extensive usage and customer feedback indicate that it generally improves implicit convergence rate as well as results when compared to the contacts normally used for explicit analysis, which will be illustrated in this paper. The intention is also to provide a theoretical basis of the contact including practical guidelines on how to use it.

2 General usage

The Mortar contact is activated by typically appending the suffix MORTAR to the automatic single-surface, automatic surface-to-surface or forming surface-to-surface keywords. It can also be run as tied and tiebreak contacts. The keywords of interest are

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*CONTACT_FORMING_SURFACE_TO_SURFACE_MORTAR
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR
*CONTACT_AUTOMATIC_SINGLE_SURFACE_MORTAR
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_TIED
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK_MORTAR
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Most parameters used for the standard forming and automatic contacts apply also to the Mortar contact, except for a few of which some will be mentioned herein. All Mortar contacts are segment to segment and penalty based and the tied and tiebreak contacts are always offset, i.e., the tie occurs on the outer surfaces of shells and not on the mid surfaces. For the forming contact the rigid tools must be meshed so that the normals are directed towards the blank, and contacts from above and below must be separated into two or more interfaces because contact can only occur from one side of the blank for a given contact interface. For the forming contact, rigid shells on the master side have no contact thickness. This is not the case for automatic contacts, here there are no restrictions on the mesh and even rigid shells have contact thickness. For automatic contacts, edge contact with flat edges is always active. The more advanced features applicable to other standard contacts but not to the Mortar contact include friction tables and orthotropic friction, the friction model here is the standard isotropic Coulomb friction law with constant frictional coefficient. On the other hand it possesses features of particular interest to implicit analysis and that will be presented in upcoming sections. It is supported in both smp and mpp but neither the option MPP nor the parameter SOFT apply, bucket sort is performed every cycle and the smp IGNORE flag applies. To summarize it is a contact algorithm especially intended for implicit analysis.

3 Theory and implementation

3.1 Kinematics

The Mortar contact is theoretically treated as a generalized finite element where each *element* in this context consists of a pair of contact segments. The friction model in the Mortar contact is a standard Coulomb friction law but here merely adds complexity to the presentation and is therefore omitted for the sake of clarity, see [3] for a more comprehensive discussion. Each of the two segments has its isoparametric representation inherited from the underlying finite element formulation, so the coordinates for the slave and master segments can be written

$$\mathbf{x}_s = N_s^i \mathbf{x}_i, \quad \mathbf{x}_m = N_m^j \mathbf{x}_j$$

where summation over repeated indices is implicitly understood. The kinematics for the contact element can be written as the penetration

$$d = \mathbf{n}_s^T \left(\mathbf{x}_s - \overline{\mathbf{x}}_m \right)$$

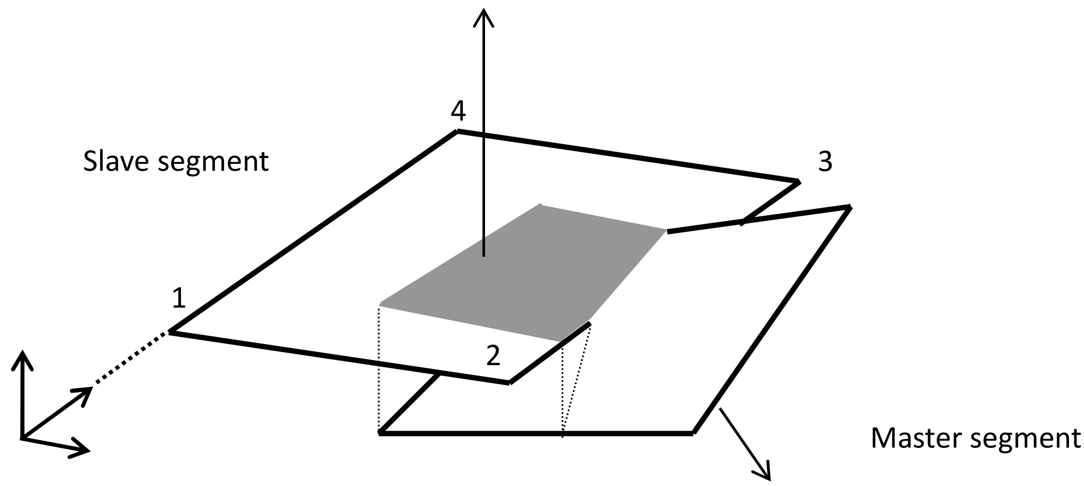

Fig 1: Schematic representation of the generalized contact element.

where $\mathbf{n}_s$ is the slave segment normal and $\overline{\mathbf{x}}_m$ is the projected point on the master segment along the slave segment normal. This is illustrated in Fig. 1 above.

3.2 Contact pressure and release

The contact pressure is given by the constitutive law

$$\sigma_c = \alpha \varepsilon K_s f\left(\frac{d}{\varepsilon d_c}\right)$$

where

$$\alpha = \text{stiffness scaling factor (SFS * SLSFAC)}$$
$$K_s = \text{stiffness modulus of slave segment}$$
$$d = \text{penetration distance}$$
$$\varepsilon = 0.03$$
$$d_c = \text{characteristic length}$$

and

$$f(x) = \begin{cases} \frac{1}{4}x^2 & x < \frac{1}{4\varepsilon} \\ \text{cubic function that depends on IGAP} & \frac{1}{4\varepsilon} \le x \end{cases}$$

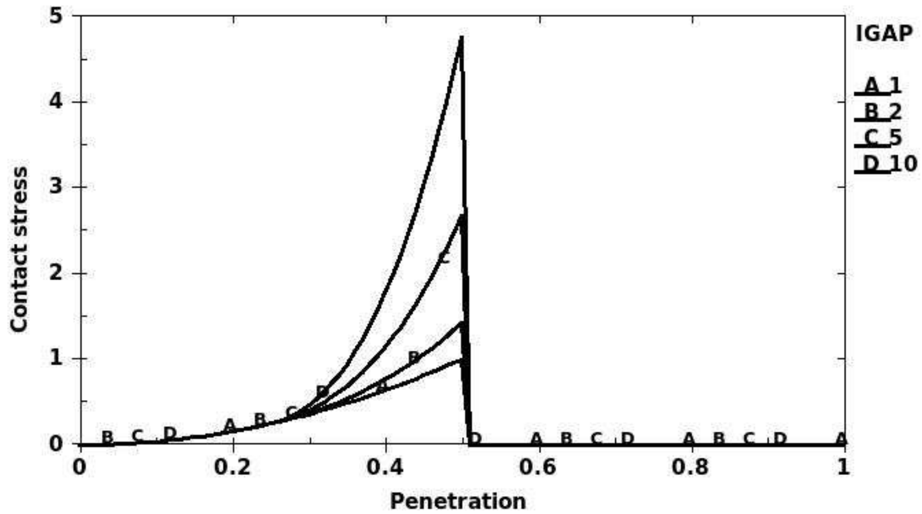

Fig. 2: The contact stress as function of relative penetration depth, the influence of IGAP is shown.

As can be seen from this, the contact stiffness is based on the slave side material stiffness and it is therefore recommended to always put the weak part as the slave side in Mortar contact. For contact between rubber and steel for instance, put the rubber on the slave side. It is furthermore recommended to use parts or part sets in the contact definitions.

The characteristic length is for shells the shell element thickness and for solids it is the shortest element edge of the part constituting the slave side of the contact. The latter may lead to unrealistically high or low contact stiffness and it is therefore recommended to explicitly set this characteristic length on the parameter SST for slave sides consisting of solid elements. Unfortunately this will also affect the shell contact thickness if shells are part of the slave side, whence it is recommended to separate shells and solids into different contact interfaces if possible.

The contact pressure is initially a parabolic function of the penetration distance which asserts the smoothness desired for implicit analysis. For some problems the contact stress can locally be very high which as a consequence leads to large penetrations. If the penetration in an equilibriated configuration becomes larger than half the characteristic length, the contact is released for subsequent implicit steps which may destroy the results of the simulation. This is prevented by increasing IGAP which progressively increase the contact stress for penetrations larger than a quarter of the characteristic length. This is illustrated in Fig. 2. Contact release can also be prevented by increasing the stiffness scaling factor SFS, but this also affect small penetrations and consequently the overall implicit performance.

In implicit analysis it is almost inevitable to run into convergence problems, especially when contacts are involved. When this happens the user usually craves for information on what's gone wrong. For the Mortar contact, detailed information on penetration distance and potential contact release can be requested through MINFO=1 on *CONTROL_OUTPUT. With this option information on largest penetration, both absolute and relative, is given in the message files after each equlibriated step, including a warning if penetration is close to being released. It also reports the elements with largest penetrations which makes it easy to locate critical areas of the model in LS-PRE/POST.

3.3 Finite element consistent force

To end the theoretical description of the contact, the principle of virtual work leads to the following expression of the finite element contact forces

$$\mathbf{f}_i = \int_{S \cap M} \frac{\partial d}{\partial \mathbf{x}_s^i} \sigma_c dS, \quad \mathbf{f}_j = \int_{S \cap M} \frac{\partial d}{\partial \mathbf{x}_m^j} \sigma_c dS$$

which involves a proper integration of shape functions over the intersection of the slave and master segment. This is unique for the Mortar contact and is something that contributes to its accuracy but also to its relative expense.

3.4 Initial penetrations

Initial penetrations are always reported in the message files, including the maximum penetration and how initial penetrations are to be handled. The IGNORE flag governs the latter and the options are

IGNORE=0	Initial penetrations will give rise to initial contact stresses, i.e., the slave contact surface is not modified
IGNORE=1	Initial penetrations will be tracked, i.e., the slave contact surface is translated to the level of the initial penetrations and subsequently follow the master contact surface on separation until the unmodified level is reached
IGNORE=2	Initial penetrations will be ignored, i.e., the slave contact surface is translated to the level of the initial penetrations, optionally with an initial contact stress governed by MPAR1
IGNORE=3	Initial penetrations will be removed over time, i.e., the slave contact surface is translated to the level of the initial penetrations and pushed back to its unmodified level over a time determined by MPAR1
IGNORE=4	Same as IGNORE=3 but it allows for large penetrations by also setting MPAR2 to at least the maximum initial penetration

The use of IGNORE depends on the problem, if no initial penetrations are present there is no need to use this parameter at all. If penetrations are relatively small in relation to the maximum allowed penetration, then IGNORE=1 or IGNORE=2 seems to be the appropriate choice. For IGNORE=2 the user may specify an initial contact stress small enough to not significantly affect the physics but large enough to eliminate rigid body modes and thus singularities in the stiffness matrix. The intention with this is to constrain loose parts that are initially close but not in contact by pushing out the contact surface using SFST and applying the IGNORE=2 option. It is at least good for debugging problems with many singular rigid body modes. IGNORE=3 is the Mortar interference counterpart, used for instance if there is a desire to fit a rubber component in a structure. With this option the contact surfaces are restored linearly in time from the beginning of the simulation to the time specified by MPAR1. A drawback with IGNORE=3 is that initial penetration must be smaller than half the characteristic length of the contact or otherwise they will not be detected in the first place. For this reason IGNORE=4 was introduced where initial penetrations may be of arbitrary size, but it requires that the user provides crude information on the level of penetration of the contact interface. This is done in MPAR2 which must be larger than the maximum penetration or otherwise and error termination will occur. IGNORE=4 only applies to solid elements at the moment.

4 Examples

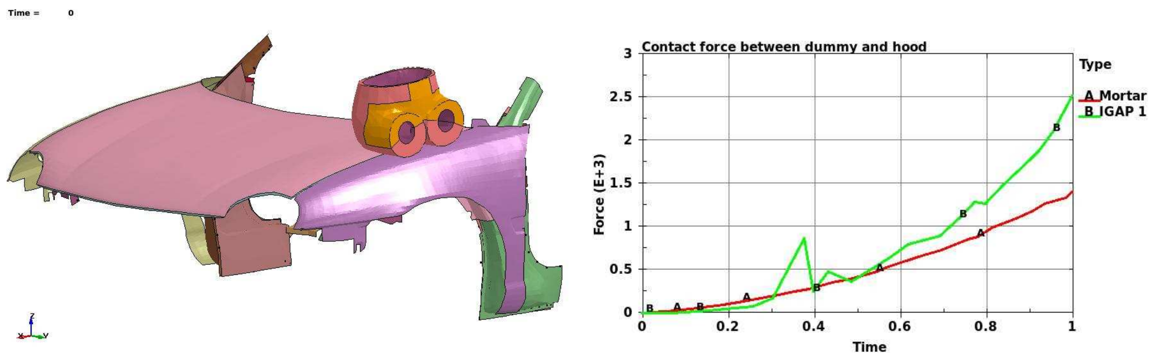

Fig. 3: Quasi-static placement of a dummy on hood, graph shows the irregularities in response often associated with the use of stiffness smoothing (IGAP>1 for standard contacts)

4.1 Dummy on hood

The first example is the quasi-static placement of a dummy to a car hood as shown in Fig. 3, the motion of the dummy is prescribed and the contact force between the dummy and hood is monitored. This problem was solved with different types of contacts and with different types of parameter settings. Out of the ones tested, only the Mortar contact and contacts with stiffness smoothing solved the problem, and for these the Mortar contact took about 10-15% longer time. Stiffness smoothing however, activated by putting IGAP>1 on standard contacts, augments the stiffness matrix causing an inconsistency between the actual response and its differential which may lead to inaccuracies in the final result. This is shown in Fig. 3 as the contact force is not as smooth as for the Mortar case, stiffness smoothing typically calls for tighter convergence criteria and/or thorough checking of the results. It is here worth repeating that stiffness smoothing does not apply to the Mortar contact but IGAP has another meaning as presented earlier.

4.2 Rubber component fit

The second example is the fitting of a rubber component shown in Fig. 4. The initial penetrations are here large enough for the contact to not detect all of them which makes use of the IGNORE=4 option. The problem consists of 468310 solid elements and was solved in 4 hours and 15 minutes on 12 processors. In Fig. 5 the elimination of initial penetrations is illustrated in a section cut of the initial and final configurations.

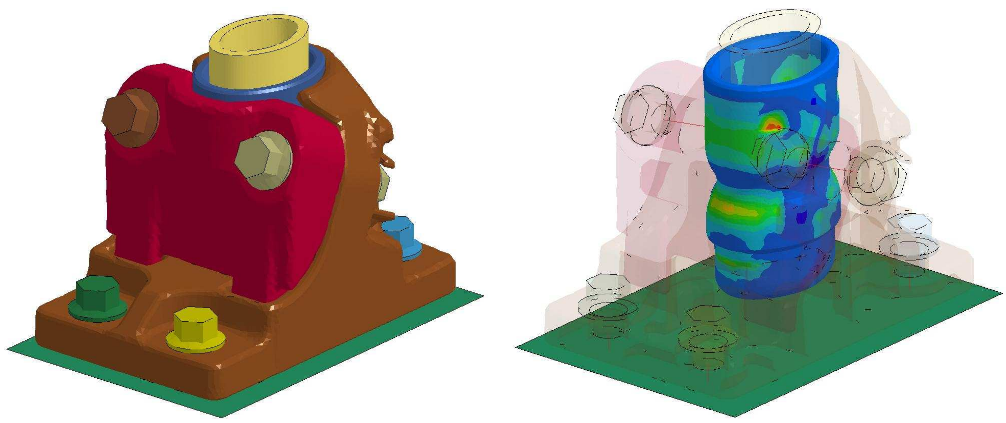

Fig. 4: Fit of rubber component, pressure is fringed. Courtesy of Volvo Group Trucks Technology Advanced Technology and Research.

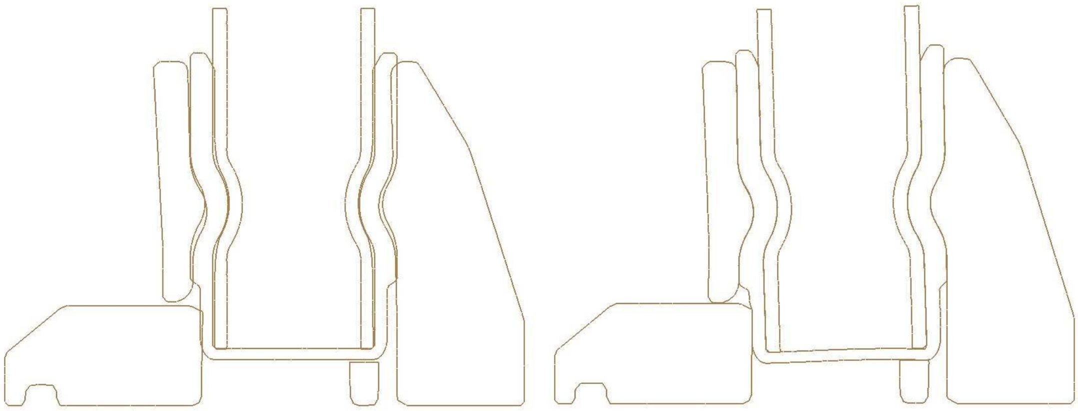

Fig. 5: Initial penetrations and penetrations eliminated in the final configuration.

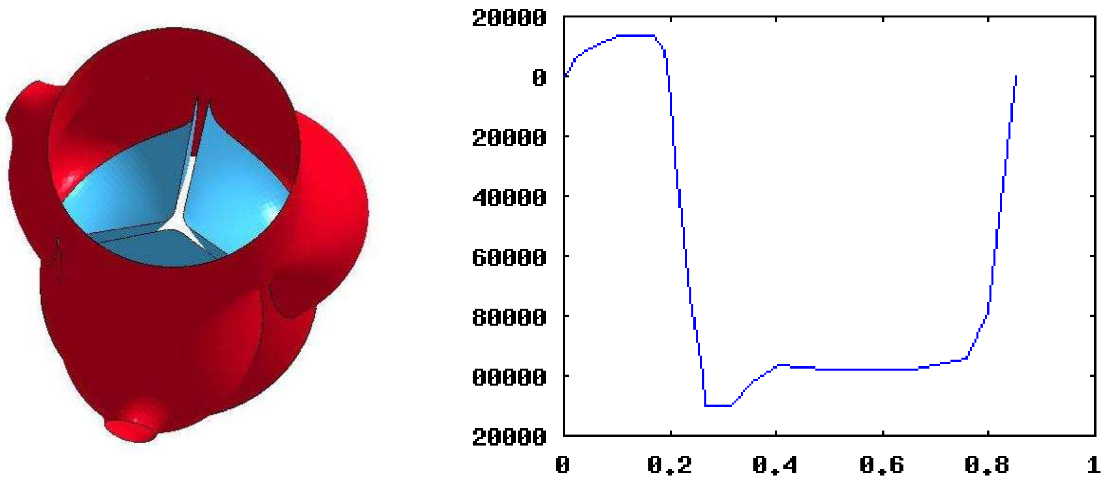

Fig. 6: Initial configuration of heart valve together with graph of pressure boundary condition for the CFD solver. Courtesy of Livermore Software Technology Corporation (LSTC).

4.3 Heart valve

The final example is taken from biomechanics and is the simulation of a systolic cycle of a synthetic heart valve. Three cavities and three leaflets are modelled using shell elements with a simple elastic material and an incompressible fluid is driven by a pressure boundary constraint that together with a strong fluid structure coupling is causing the cavities to open and close, see Fig. 6 for an illustration. The contact problem in itself is trivial, the problem here is that the CFD solver requires that the contact state is resolved to a certain degree of accuracy to allow for a robust remeshing of the fluid mesh. This is achievable at the moment only by using the Mortar contact. In Fig. 7 the opening and closing of the leaflets is shown as a sequence.

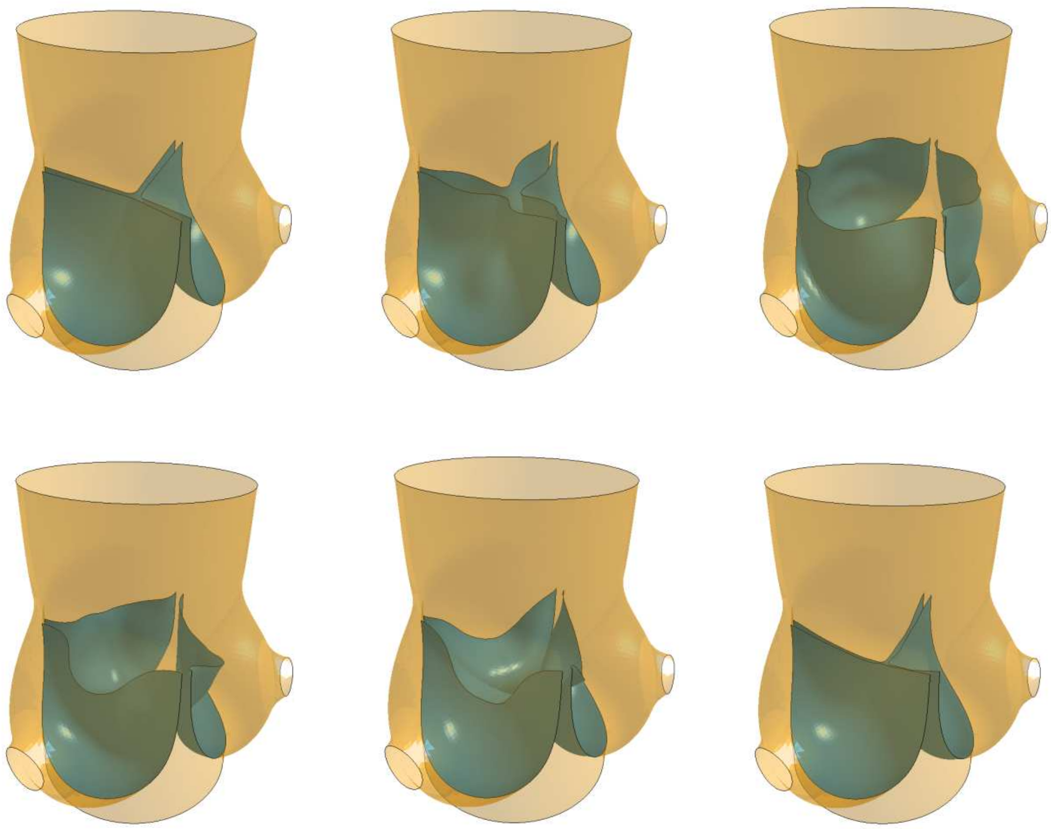

Fig. 7: Sequence showing the opening and closing of the cavities when interacting with the fluid.

5 Conclusions

The Mortar contact is available in LS-DYNA as a robust and accurate contact algorithm for implicit analysis. It has shown to provide solutions to problems that fail using other contact algorithms and other softwares. Using the Mortar contact does not guarantee success in implicit analysis, but when convergence failure is a fact the user may request sufficient information about the contact state (and the implicit solver) that will aid in eliminating the potential source(s) to the malicious behavior.

6 Acknowledgements

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7 References

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