POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

Simulation of Dynamic Ice Indentation Failure

Kuutti, Juha[1], Kolari, Kari[1]

[1]VTT Technical Research Centre of Finland, Espoo, FINLAND

Abstract

Structural vibration caused by ice crushing is an important phenomenon which has to be taken account in the design of structures. The crushing failure mode and rate can often be the cause of the vibration. Beside the dynamic properties of structure the velocity of ice is known to be important variable in the process.

Simulation of crushing is a challenging task. During the continuous crushing process initially intact ice is broken into flakes and fragments of different sizes. The interaction of fragments with structure and intact ice must be considered in the analysis as previous failures affect subsequent failures. The cohesive surface methodology is known to be suitable for the numerical analysis of fragmentation.

The cohesive surface methodology is applied in this paper. The methodology is based on inserting possible fracture planes between all elements of the simulation model. This limits the cracking to element boundaries but allows fragmentation and subsequent interaction of fragments. A new rate dependent stress-separation law has been proposed and implemented into the explicit solver of Abaqus software. The applied method has been verified by simulating structure-ice interaction with varying ice velocity. The simulations in this paper focus on determining velocity effects of ice crushing.

The simulated results have been compared with the existing laboratory experiments. The failure modes obtained in the simulation were similar to the modes obtained in the experimental tests. In the simulation the contact pressure was found to be not evenly distributed but concentrated into spots. The location of the hot spot was varying during the simulations as it is in the experiments. The highest load was obtained at the beginning of the simulation, similar as in the experiments. After initial failure the results show fluctuations in the contact force. The simulation results are promising.

1. Introduction

Failure initiation, propagation and fragmentation of intact ice in ice-structure interaction is a complex process that can include multiple failure modes from crushing to bending. Laboratory and in-situ experiments can capture these modes but transferring the experimental results to other cases can be difficult. Experiments are often used in calibrating numerical models that can be then applied to other scenarios with same fracture behaviour.

The finite element method is still the most widely applied technique in numerical analyses. Accurate modelling of ice crushing requires advanced simulation methods to capture different failure modes. The birth, growth and interaction of multiple cracks lead to material fragmentation that needs to be captured by the simulation method. The separated material fragments needs to be included in the analysis as they affect subsequent failures.

In this work the laboratory ice crushing experiments reported by Määttänen et al. (2011) are studied using the cohesive surface methodology expanding the work presented by Kuutti et al. (2013). These simulations are now continued to study the dynamic effects of the process. In the experiments medium scale ice blocks were pushed against vertical structure and contact pressures were measured using a tactile pressure sheet. In the work of Kuutti et al. (2013) the experiments were modelled numerically to study the applicability of the cohesive surface methodology. Effects of mesh density, mesh layout and different material softening behaviours were studied. Sequential ice failure process where each failure event affects the next was realistically simulated and simulation results agree with experimental observations. High pressure zone type contact was obtained in the simulations and the simulated crushing forces are in agreement with the experimental results.

2. Ice failure and ice-structure interaction

Ice-structure interaction is a complex process where ice can experience multiple failure modes. Ice breaks into smaller pieces that can stay in the failure region or clear away. Ice can fragment into several big blocks with a global failure mode or pulverize into fine powder with multiple local failures. Ice compressive failure most notably produces small-grained crushed ice but the process contains at least four distinctive failure mechanisms. They are microcracking, macrocracking with flake explosion, macrocracking with flake progressive failure and rapid cascade of macrocracks (Daley et al. 1998). In compressive failure all failure modes are present. Some are more dominating than others and mode can change throughout the process. Often if the contact surface is flat the process is confined and the ice will fail by microcracking. Flaking will occur after this when the shape of the fracture region has become irregular. According to Daley et al. (ibid) ice failure is a continuous event where each failure event changes the geometry and boundary conditions and effects next failure event. In many experiments the contact between ice and structure is found to be concentrated on either specific areas, i.e. hot spots (Jordaan et al. 2008), or a narrow band, i.e. line-like contact (Joensuu and Riska 1989). The location of the contact region is observed to move as the crushing progresses. The typical force time series during crushing is saw-tooth shaped caused by repeating fracture cycles (Jordaan et al. 2008).

Modelling of ice crushing and fragmentation

Natural ice is a complex material that shows both ductile and brittle behaviour depending on strain rate among other variables. Many constitutive models for ice under ductile and brittle range have been proposed (Ashby and Sammis 1990, Xiao and Jordaan 1996, Zhan et al. 1996). Continuum models are not suitable for continuous ice-structure interaction simulation directly without modifications. Simulation of the full interaction process requires first the modelling material failure initiation, propagation and the orientation of the failure. This can be handled by a suitable constitutive model. In addition, the simulation requires the modelling of the fragmentation such that new free surfaces are created in the model and the modelling of the subsequent interaction of fragments, structure and the intact ice. This demands additional techniques. The simplest additional technique is element deletion that creates the required explicit free surfaces and discrete fragments but also violates the conservation of mass and creates empty voids in the model. Specifying the crack paths in the model beforehand can be used to avoid element deletion but this approach is not suitable for modelling severe cracking and fragmentation as crack paths cannot be predicted.

Several techniques have been proposed that are able to produce near arbitrary cracking in the simulation model. A straightforward technique is the cohesive surface methodology where each element is surrounded with cohesive elements that are able to transmit tractions across the interface and fail when sufficient loading is applied. The method has been applied for example by Xu and Needleman (1994) Camacho and Ortiz (1996) and Tijssens et al. (2000). The method has found to be suitable for modelling severe cracking although some mesh dependency has been observed. In newer approaches the discontinuity can be represented with internal degrees of freedom in the original mesh such as in the extended finite element method (XFEM) The crack is then more sophisticatedly modelled but the capturing the full crushing process is more difficult due to limitations in treatment of multiple interacting and propagating cracks and interaction of broken-off particles.

Most numerical studies of ice-structure interaction are mainly concentrated only the first stages of ice failure and ice-structure interaction process and post-failure behaviour are neglected, e.g. Jordaan et al. (2008) and Horrigmoe and Andersen (1993). More recent studies have focused on the fragmentation and interaction of fragments (Derradji-Aouat 2005, Selvadurai 2009, Gürtner 2009, Paavilainen et al. 2011, Kuutti and Kolari 2012). Discrete methods efficiently handle the interaction of large number of fragmented particles but the crushing process itself is only approximately represented (Paavilainen et al. 2011, Polojärvi and Tuhkuri 2009).

Cohesive zone models pioneered by Hillerborg et al. (1976) are often used in modelling the softening behaviour of ice. In these models the microcracking is modelled with a traction-separation curve that represents material resistance to the amount of microcracking. Cohesive models have been applied for also modelling ice fracture extensively, e.g. Mulmule and Dempsey (1997) and in ice-structure interaction simulations (Gürtner 2009, Konuk et al. 2009a, Konuk et al. 2009b) who studied the full scale interaction between level ice and a cylindrical structure using a finite element model in which solid brick elements were tied together using cohesive ties at all possible element boundaries. Ice deformation process in a global scale was simulated realistically.

Ice crushing process and ice-structure interaction is simulated in this work by utilizing the cohesive surface methodology. Cohesive ties, i.e. possible fracture planes, are inserted to the FE mesh at all element boundaries. The ice block can thus fracture during crushing by spalling and flaking.

3. Simulation of ice crushing

The cohesive surface methodology was applied for modelling ice crushing. The methodology is based on inserting breakable bonds between each bulk element in the model as described by Tijssens et al. (2000). The method allows modelling large scale material fragmentation and interaction of fragmented particles as it produces free surfaces after cracking. The cohesive elements model the fracture process zone and the cohesive material law relate the stress over the crack with crack opening. In the cohesive surface methodology explicit cracking is a natural solution of the mathematical model without any assumptions on crack trajectories. Global response of the model is anisotropic due to different crack orientations although the local softening model for individual cohesive element is isotropic. A single cohesive element carries only compressive and tensile loads normal to element plane and in-plane shear loads. Loading in other directions is carried by the bulk elements and other cohesive elements with different orientations. The mesh orientation effects are avoided by using an unstructured mesh.

Analysis model

Ice blocks of the size of 1200×800×190 mm where crushed against a vertical structure in the experiments by Määttänen et al. (2011). In this work the case is analysed using a planar model of size 190×800 mm that represents a thin sheet in the middle of the specimen. The block was meshed using triangular elements that were surrounded by cohesive elements at all sides in the crushing region. The mesh is shown in Figure 1. Bulk element size in the crushing region was approximately 20 mm. Thickness of the cohesive element tying the bulk elements together was specified to be 1 % of the bulk element size.

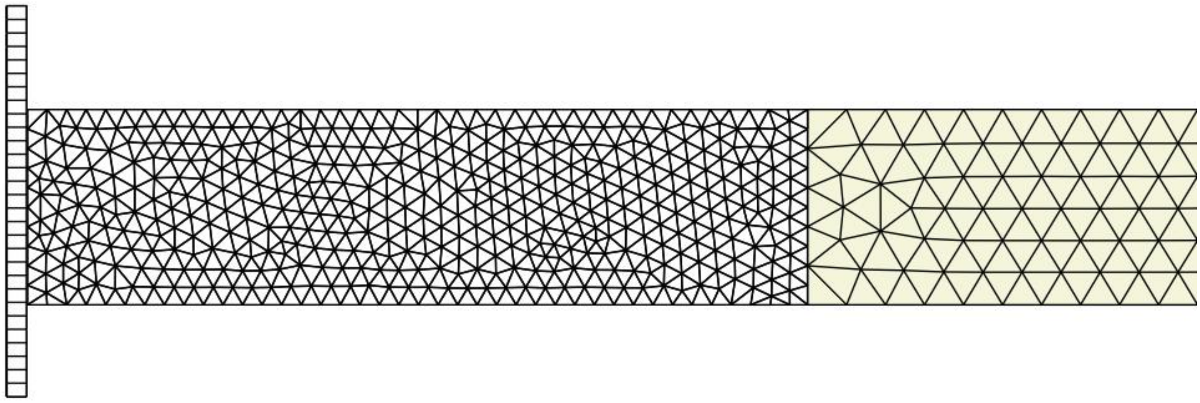

Figure 1. Simulation model. Denser mesh and cohesive elements are inserted in the crushing region and coarser bulk mesh away from the wall where crushing is not expected.

In the work of Kuutti and Kolari (2013) the effects of mesh size, layout and softening law were studied. In the simulations presented in this work a medium sized unstructured mesh was utilized together with a linear softening law. The crushing velocity of ice was varied from 6 mm/s to 162 mm/s. At least 150 mm of crushing was simulated with each model. A total of 8 crushing simulations were carried out with four velocities and both rate-dependent and rate-independent material behaviours.

Material properties

The cohesive elements utilized a linear softening law for tension and shear. The cohesive traction increases linearly as a function of separation until the failure stress is reached. After initial failure the cohesive stress decreases to zero linearly as a function of separation. The magnitude of separation that causes zero cohesive stress is calculated from the given fracture energy. The effect of strain rate is studied by utilizing a dynamic strength increase factor for failure stress.

The compressive behaviour was fully elastic. Isotropic elasticity and ideal plasticity was defined for the bulk elements. All applied material properties are given in Table 1. They are based on the values given by Määttänen et al. (2011). The value of the shear strength was not measured and the value used in the analyses was calculated based on the measured density as proposed by Timco and Weeks (2010). The fracture energy was taken as a typical value for ice.

Table 1. Material parameters applied in the simulations

Cohesive elements		**Bulk elements**	
Density	860 kg/m^3	Density	860 kg/m^3
Elastic modulus	7.0 GPa	Elastic modulus	7.0 GPa
Failure stress, tension	0.85 MPa	Poisson ratio	0.3
Failure stress, shear	0.91 MPa	Yield stress	2.6 MPa
Fracture energy	30 J/m^2		

The dynamic strength increase factor (DIF) affecting the failure stress is assumed to be a linearly proportional to the strain rate according to relation

$$DIF = \begin{cases} 1+\dfrac{\dot{\varepsilon}_i}{2\dot{\varepsilon}_0}, & \dot{\varepsilon}_i < \dot{\varepsilon}_0 \\ 1.5, & \dot{\varepsilon}_i \geq \dot{\varepsilon}_0 \end{cases}, \tag{1}$$

where $\dot{\varepsilon}_i$ is strain rate in either tension or shear. $\dot{\varepsilon}_0$ is a scaling parameter that is used to control the increase of the DIF. It is assumed that the strength can be increased by a maximum of 50 %. In the simulations it is assumed that the DIF is same for both tension and shear and $\dot{\varepsilon}_0 = 1\times10^{-3}$. Compressive stresses in the cohesive elements do not cause cracking and thus DIF in the compressive region is not needed. Some examples of the softening relation at different strain rates are shown in Figure 2.

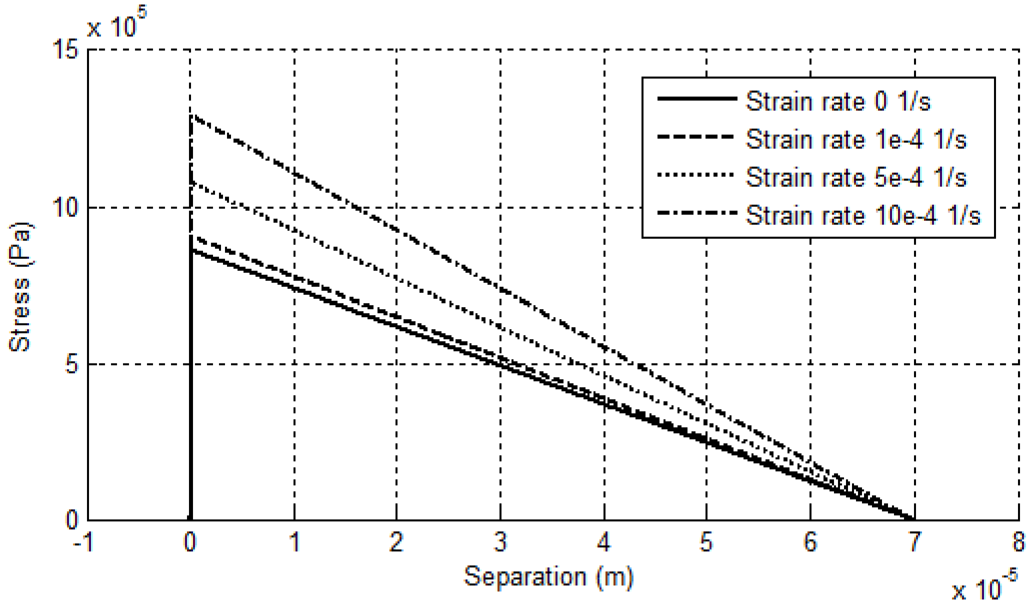

Figure 2. Examples of linear softening relations with different strain rates.

Contact was defined between all external surfaces of the model such that all new surfaces exposed due to fractures are included in the contact algorithm. Coulomb friction with friction coefficient of 0.1 was applied for all contact surfaces. In addition, buoyancy and gravity was included such that the ice block floats at the start of the simulation.

Simulated ice crushing was studied both visually from block deformations and from contact forces and contact areas. All simulations were carried out using commercial FE-software Abaqus version 6.11-1. Explicit time integration scheme was applied. Mass scaling for cohesive elements was applied to increase the stable time increment to the level of the bulk elements.

Results of crushing simulation

The simulated failure process is shown in Figure 3 through Figure 6. The progressive nature of the process where previous failures affect the later failures is clearly observed from the figures.

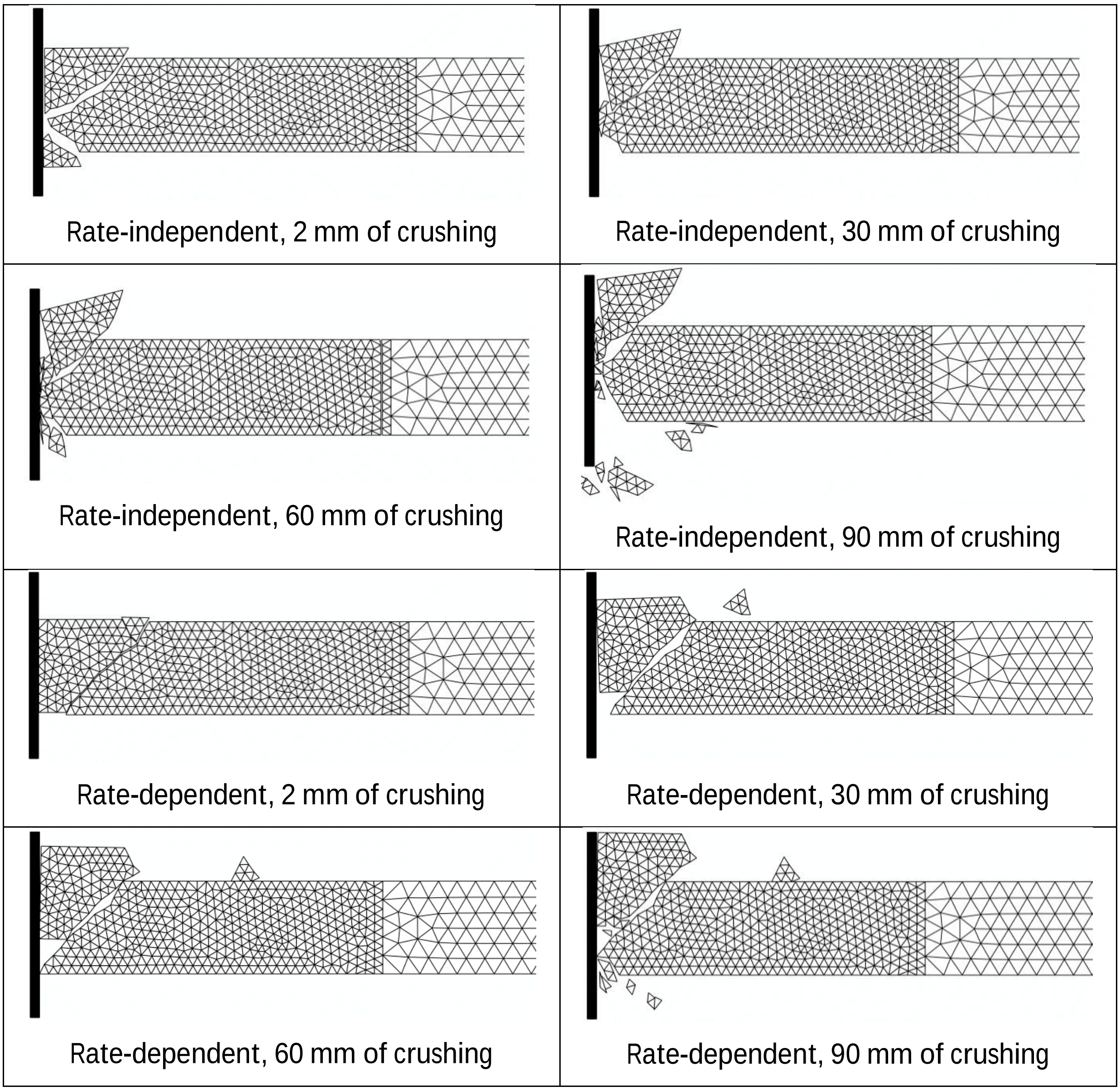

Figure 3. Simulated fracture process with crushing velocity 6 mm/s.

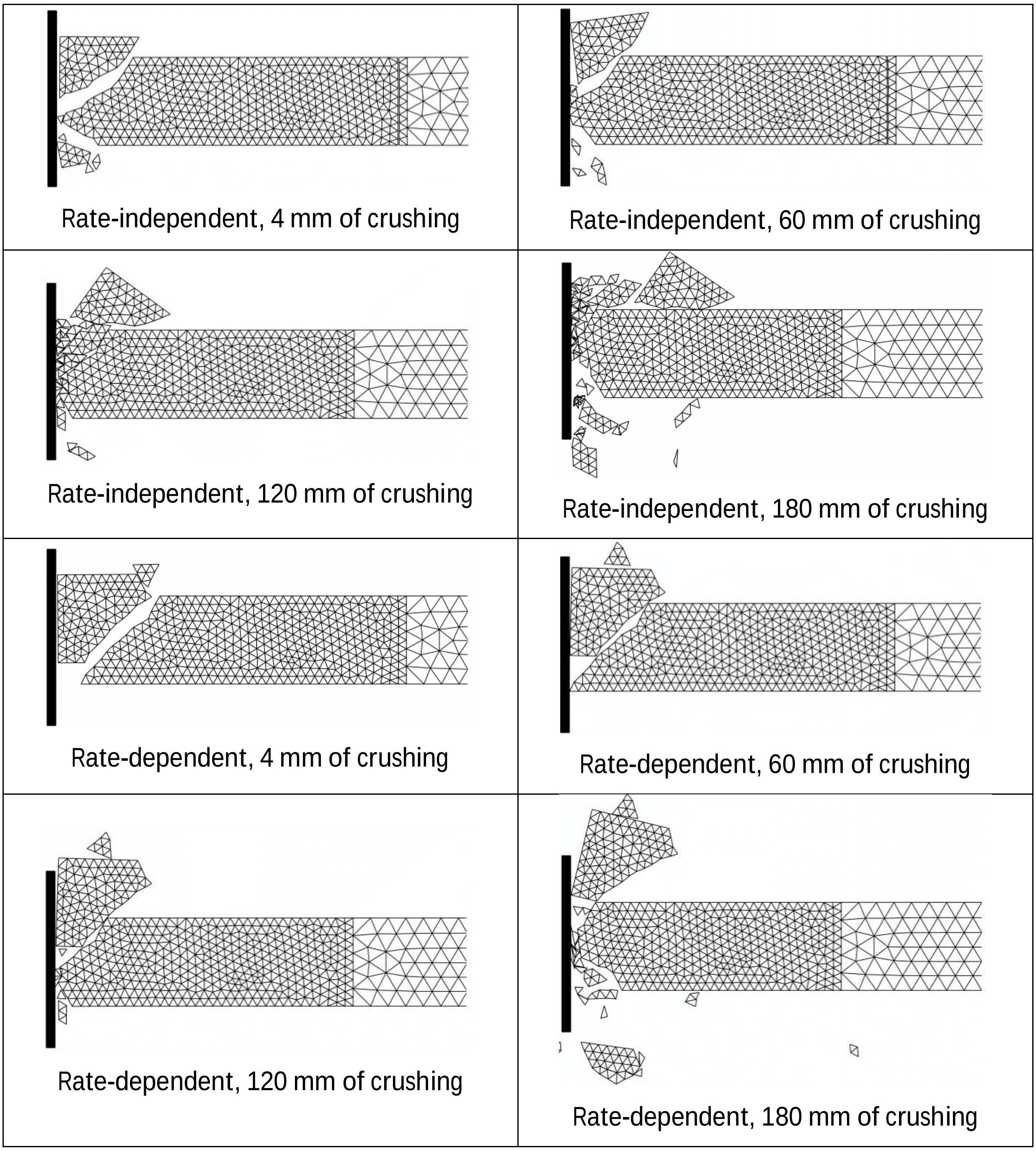

Figure 4. Simulated fracture process with crushing velocity 18 mm/s.

Initial failure mode is fairly similar for all rate-independent simulations. Two triangular fragments are separated with the upper fragment remaining in the crushing region throughout the simulations. At higher velocities the fragment has more kinetic energy that moves the fragment out of the crushing region. In the simulations with the rate-dependent model the initial failure occurs slightly away from the structure splitting the ice at a 45 degree angle. After the initial failure all simulations show a sharp beak that comes into contact with the structure in a hot-spot type contact. The initial failure is followed by subsequent smaller failures. The separated fragments are seen to fail progressively. Both small and large separated fragments are seen to remain in the contact region and affect the later fracture process. The separated flakes form a pile of rubble in the contact region. Cohesive elements beyond the crushing region were still intact indicating the local nature of the process. Bulk elements were compacted in the failure region that can be seen by the large deformation of single separated triangular elements.

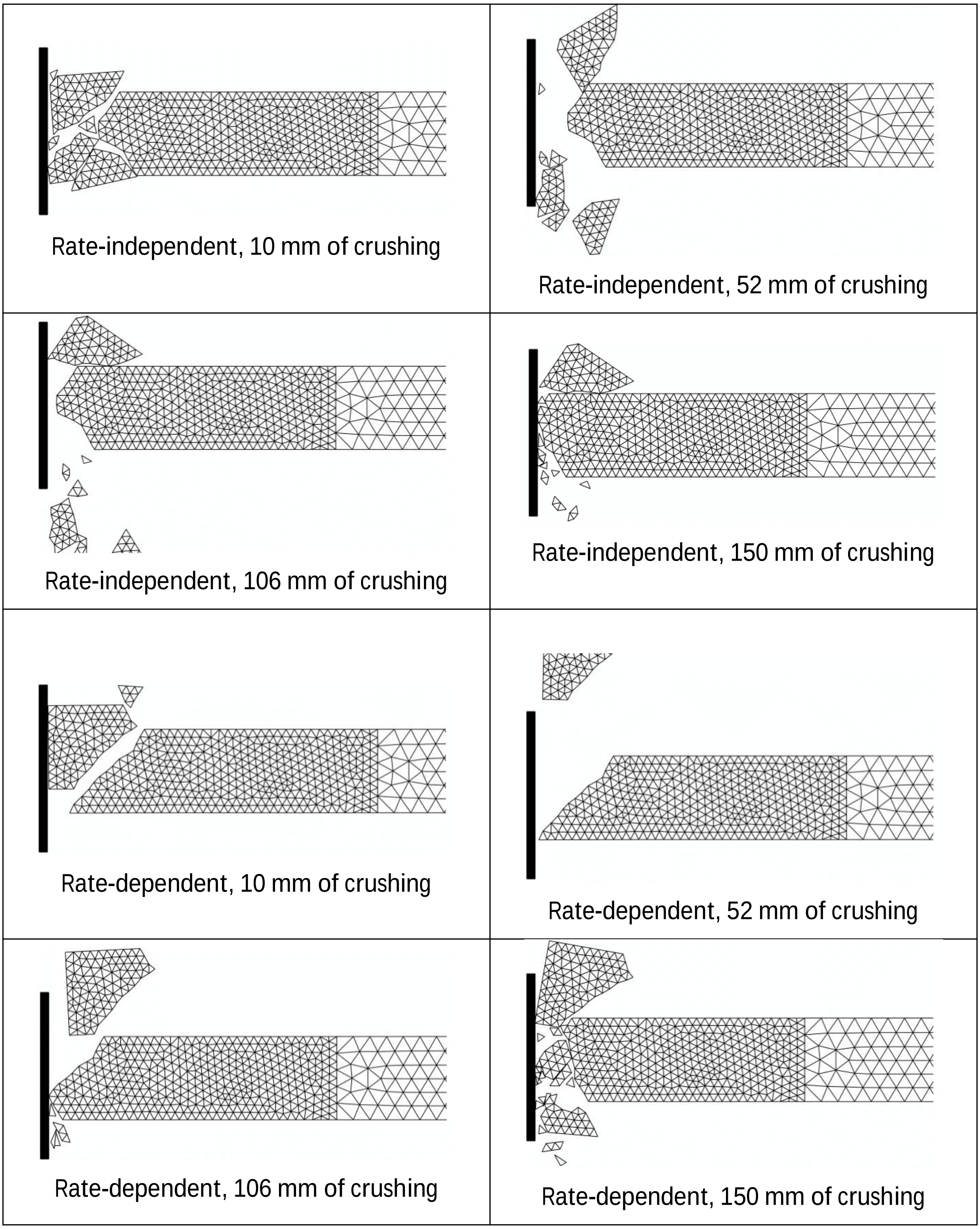

Figure 5. Simulated fracture process with crushing velocity 54 mm/s.

After initial failure the contact region was mostly smaller than the thickness of the sheet. The location and the width of the contact area are visualized in Figure 7. The figure shows the location of the structure nodes that exhibit contact pressures during one instant of time. Time axis is transformed into ice block displacement with the crushing velocity.

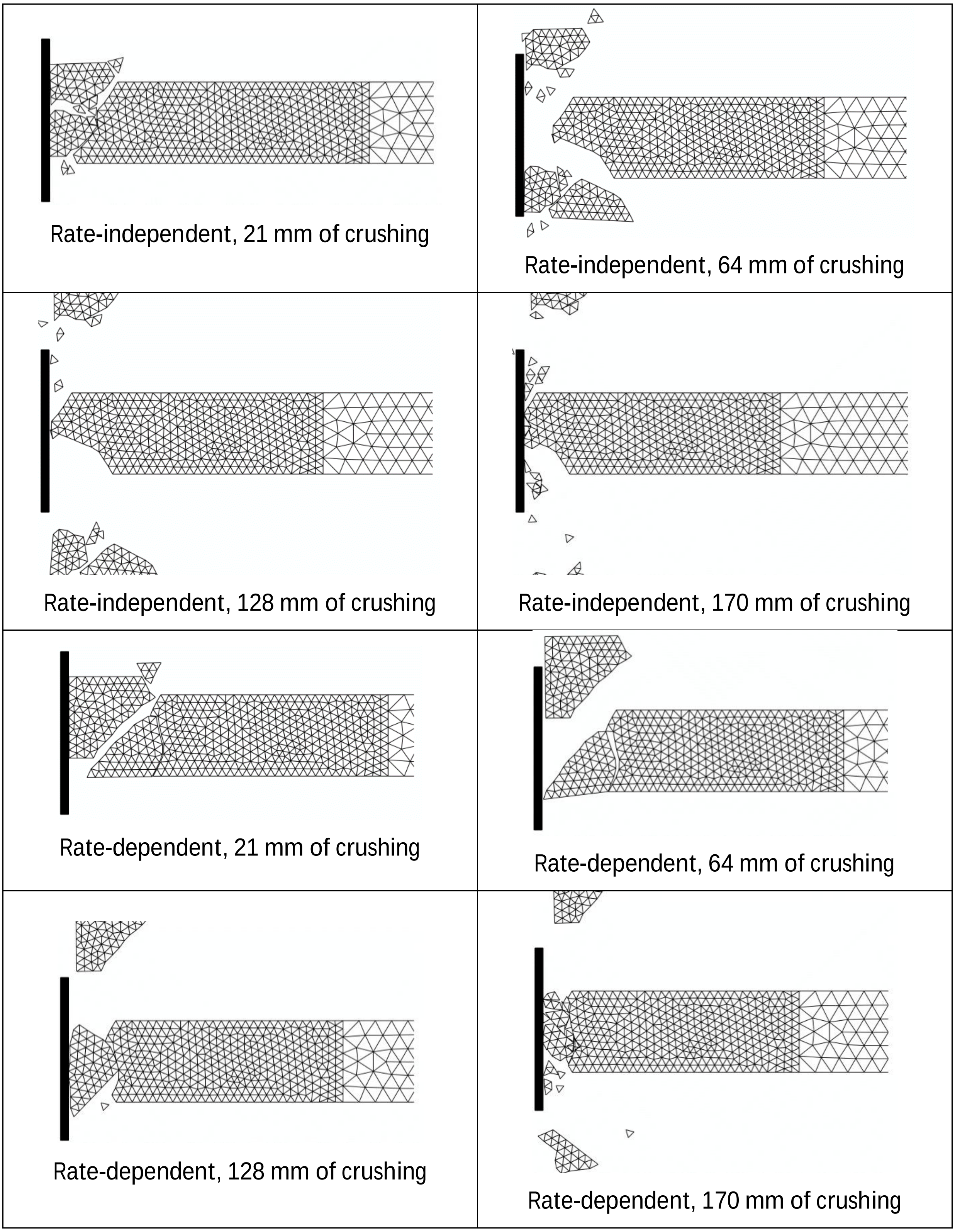

Figure 6. Simulated fracture process with crushing velocity 162 mm/s.

The contact location graphs show that the initial contact is spread over the full thickness of the ice block. The later hot-spot type contact is visible in most simulations. Location of the contact zone varied as the crushing progressed. Rubble accumulation in the crushing region can be observed by the increase of points as crushing progresses.

The force-time graphs for all simulated cases are shown in Figure 8.

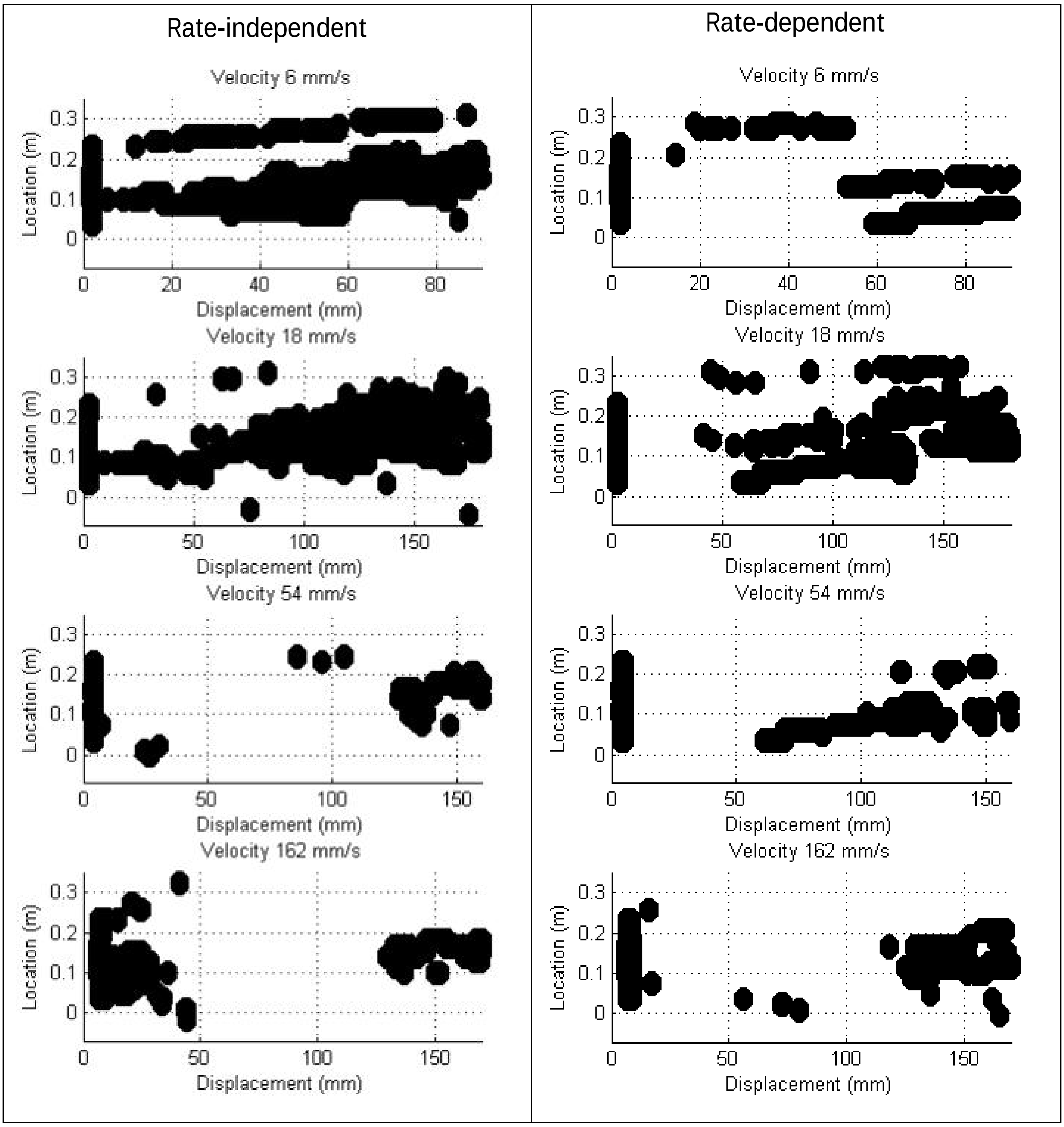

Figure 7. Contact location as a function of crushing distance for all simulated cases.

The crushing force graphs have similar characteristics for all simulations. The initial contact and failure causes the initial high peak in the graphs. In simulations where a larger fragment is separated the peak is followed by zero contact force until the ice comes into contact with the structure. In simulations with smaller crushing velocity the force graphs display multiple smaller saw-tooth shaped fracture cycles. The magnitude of the crushing force is surprisingly little affected crushing velocity.

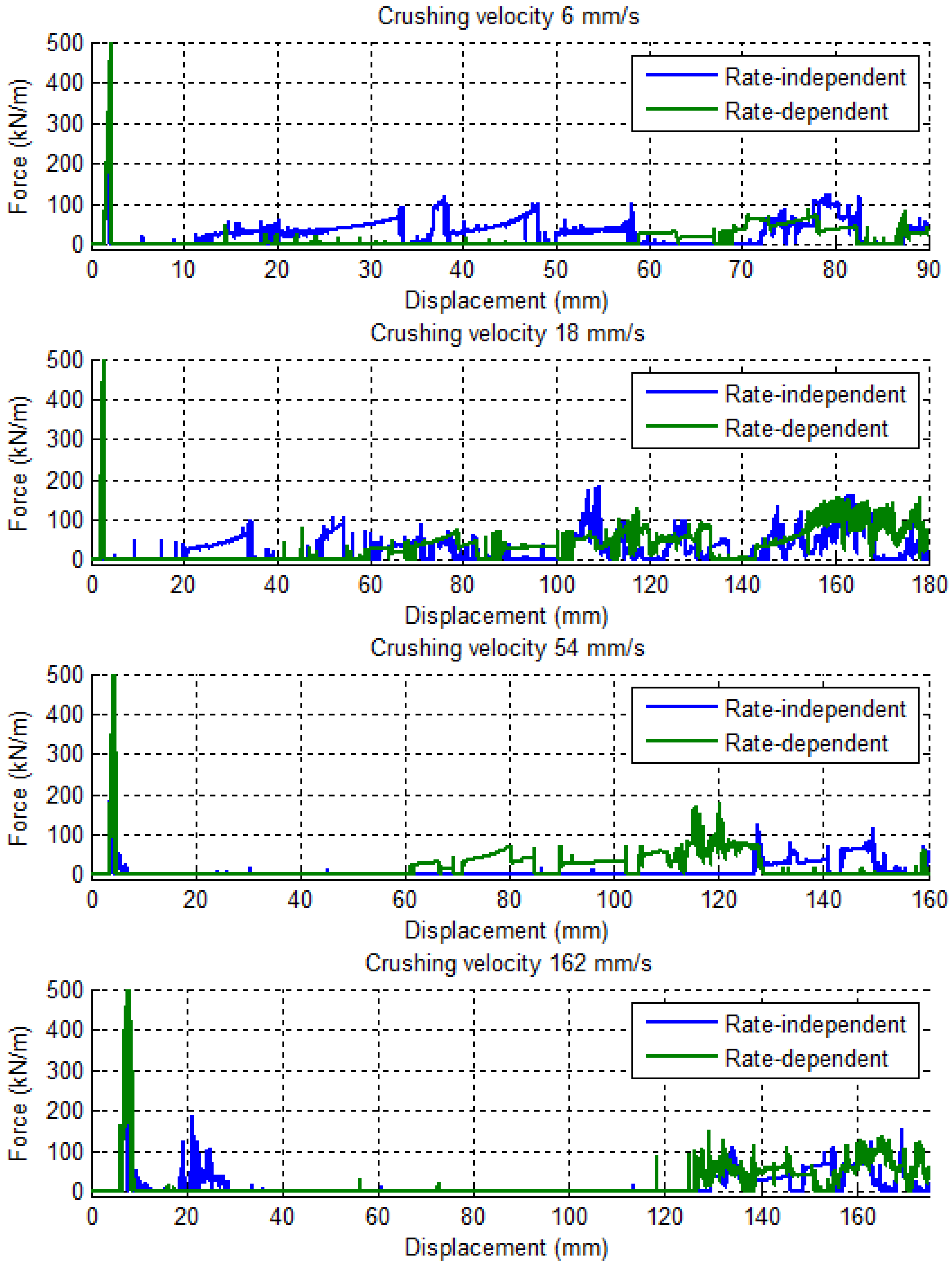

Figure 8. Simulated crushing forces for all studied cases.

Structural response analysis

Kärnä et al. (2007) state that the feedback effect between ice crushing force excitation and structural vibration response can be neglected if the ice velocity is from moderate to high and the structure's displacements are only a small fraction of ice thickness. Kärnä et al. (2007) do not provide more quantitative limits for these conditions. As the structure was rigid in the simulations, these conditions are assumed to hold when processing the simulation results. The simulated crushing loads show some typical characteristics for local ice crushing signals. Typical methods used in determining the frequency content of the signal are response spectrum method and spectral density method (Kärnä et al. 2007).

The non-dimensional power spectral densities for the simulated crushing force signals obtained with crushing velocities 6 mm/s and 18 mm/s are shown in Figure 9. Determing frequency content from force signals obtained with higher crushing velocity is not meaningful due to the small duration of the simulated signal.

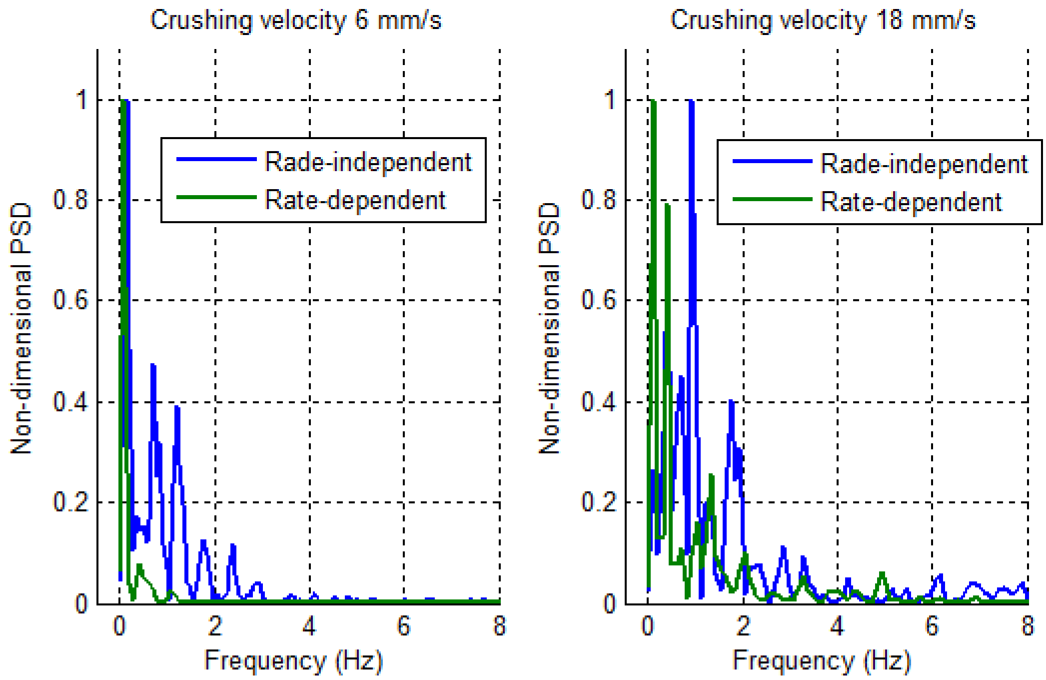

Figure 9. Power spectral density for crushing force signals simulated with crushing velocity 6 mm/s and 12 mm/s.

The response spectrum method widely applied in seismic analyses calculates the response of a single degree of freedom oscillator at several fundamental frequencies. The maximum response that can be displacement, velocity or acceleration is plotted at each studied frequency. Now the crushing forces shown in Figure 8 are used as time-dependent prescribed loading to a damped single degree of freedom oscillator. The pseudo-acceleration response spectra for all obtained contact force signals are shown in Figure 10. A constant 5 % damping was assumed in calculating the response spectra.

The power spectral densities shown in Figure 9 are similar to the typical spectral density function shape given by Kärnä et al. (2007). However due to the stochastic nature of the signal no specific frequency components stand out from the plot. The acceleration response spectra in Figure 10 show acceleration peaks at several frequencies. Simulation results obtained with higher crushing velocities show larger response at higher velocities. Due to the small duration of these force signals the response at smaller frequencies remains small.

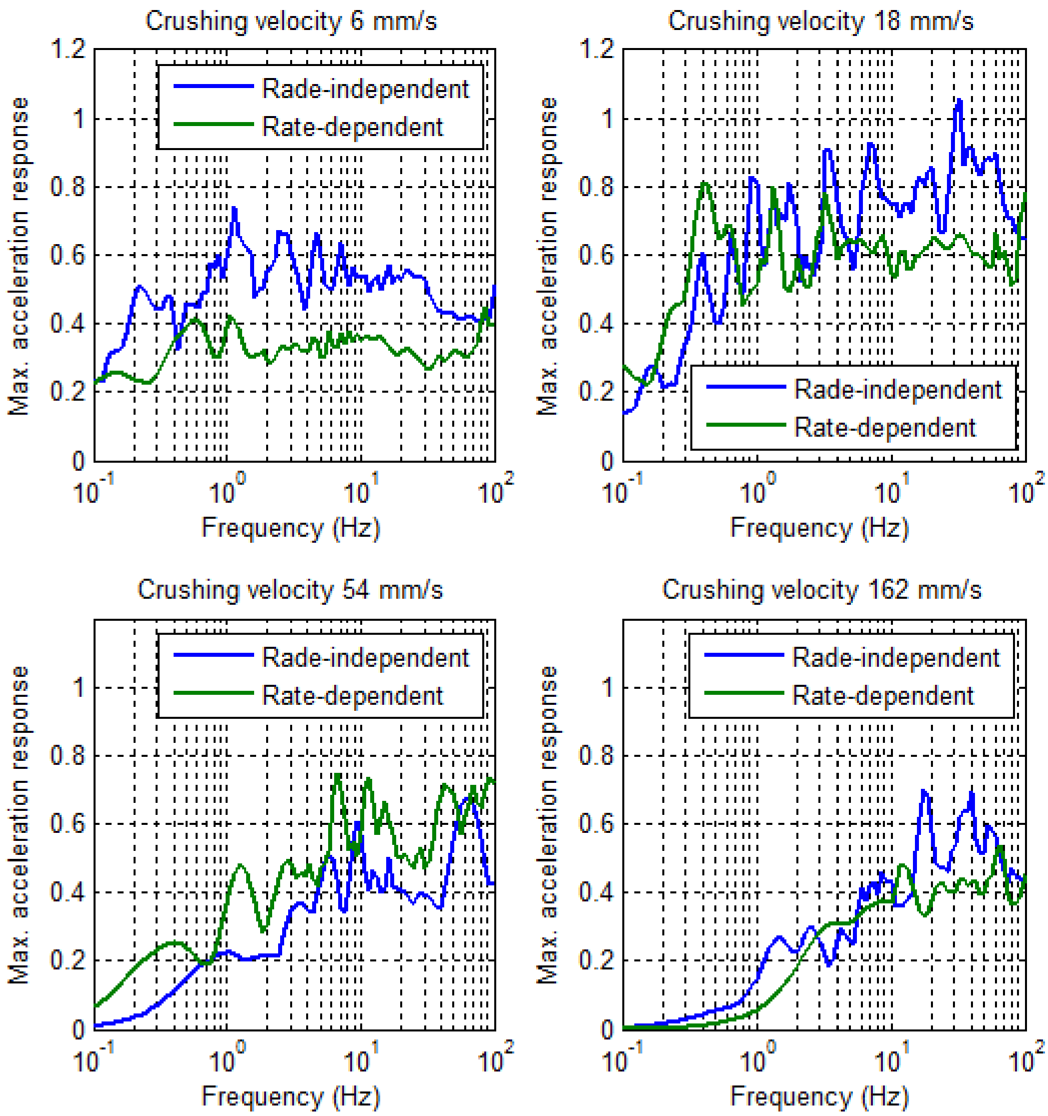

Figure 10. Acceleration response spectra obtained with all simulated crushing force histories.

4. Summary and discussion

Ice crushing against a rigid vertical structure was simulated using the cohesive surface methodology with different ice velocities and material behaviours. Ice crushing process with progressive failures was realistically simulated. The ice failure process, failure modes and failure mechanisms corresponded well with experimental findings. Fragment formation, failure and rubble formation was observed in the simulations. The progressive nature of the failure process where previous failures affect the later failures was observed as well. The simulations showed sequential hot-spot type contact with the location of the high pressure zone alternating throughout the fracture process that is also observed experimentally.

No significant increase on the crushing force levels could be observed for increasing ice velocities. The shape of the crushing load history changed as crushing velocity was increased such that larger velocities broke off larger fragments and longer zero-force periods were observed. The crushing forces showed peaks for each failure cycle with zero force levels in between the failures. This phenomenon is observed when considering local forces. The experimental results of Määttänen et al. (2011) show similar results when considering only a thin slice in the middle of the specimen. Although not presented in this paper, the results agreed with the simulated crushing force magnitudes. The line-like contact was observed both in simulations and in the experimental results. See Kuutti et al. (2013) for more detailed comparison. Frequency-domain analysis of the crushing force histories showed some periodic content was present in the simulated force signals.

An interesting development path is to apply the simulation methods in case of ice crushing against a flexible structure. In the current simulations it was assumed that the structural deformations are negligible compared to ice crushing. The susceptible structural vibrations were studied separately neglecting the possible feedback effect. In case of a sufficiently flexible structure with a suitable natural frequency the locking vibration caused by ice crushing could be obtained. The analysis would display also how the structural deformations affect the crushing process itself.

Acknowledgements

This work is supported by VTT Technical Research Centre of Finland, TEKES - the Finnish Funding Agency for Technology and Innovation and the Academy of Finland.

References

Ashby, M.F. & Sammis, C.G. 1990, The damage mechanics of brittle solids in compression, Pure and Applied Geophysics PAGEOPH, vol. 133, no. 3, pp. 489-521.

Camacho, G.T. & Ortiz, M. 1996, Computational modelling of impact damage in brittle materials, International Journal of Solids and Structures, vol. 33, no. 20-22, pp. 2899-2938.

Daley, C., Tuhkuri, J. & Riska, K. 1998, The role of discrete failures in local ice loads, Cold Regions Science and Technology, vol. 27, no. 3, pp. 197-211.

Derradji-Aouat, A. 2005, Explicit FEA and Constitutive Modelling of Damage and Fracture in Polycrystalline Ice – Simulations of Ice Loads on Structures, Proceedings of the 18th International Conference on Port and Ocean Engineering Under Arctic Conditions.

Gürtner, A. 2009, Experimental and numerical investigations of ice-structure interaction, Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Civil and Transport Engineering.

Hillerborg, A., Modéer, M. & Petersson, P. 1976, Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements, Cement and Concrete Research, vol. 6, no. 6, pp. 773-781.

Horrigmoe, G. & Andersen, R. 1993, Finite Element Analysis of Ice Sheet Indentation Considering Crushing and Time-Dependent Deformations, Proceedings - International Conference on Port and Ocean Engineering Under Arctic Conditions, POAC.

Joensuu, A. & Riska, K. 1989, Contact between ice and structure (in Finnish), Report M-88, Laboratory of Naval Architecture and Marine Engineering, Helsinki University of Technology, Espoo, Finland.

Jordaan, I.J., Wells, J., Xiao, J. & Derradji-Aouat, A. 2008, Ice crushing and cyclic loading in compression, IAHR Symposium on Ice, Vancouver, Canada.

Kärnä, T., Qu, Y., Bi, X., Yue, Q. & Kuehnlein, W. 2007, A spectral model for forces due to ice crushing, Journal of Offshore Mechanics and Arctic Engineering, vol. 129, no. 2, pp. 138-145.

Konuk, I., Gürtner, A. & Yu, S. 2009a, A cohesive element framework for dynamic ice-structure interaction problems - Part I: Review and formulation, Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE.

Konuk, I., Gürtner, A. & Yu, S. 2009b, A cohesive element framework for dynamic ice-structure interaction problems - Part II: Implementation, Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE.

Kuutti, J. & Kolari, K. 2012, A local remeshing procedure to simulate crack propagation in quasi-brittle materials, Engineering Computations (Swansea, Wales), vol. 29, no. 2, pp. 125-143.

Määttänen, M., Marjavaara, P., Saarinen, S. & Laakso, M. 2011, Ice crushing tests with variable structural flexibility, Cold Regions Science and Technology, vol. 67, no. 3, pp. 120-128.

Mulmule, S.V. & Dempsey, J.P. 1997, A Viscoelastic Fictitious Crack Model for the Fracture of Sea Ice, Mechanics Time-Dependent Materials, vol. 1, no. 4, pp. 331-356.

Paavilainen, J., Tuhkuri, J. & Polojärvi, A. 2011, 2D numerical simulations of ice rubble formation process against an inclined structure, Cold Regions Science and Technology, vol. 68, no. 1-2, pp. 20-34.

Polojärvi, A. & Tuhkuri, J. 2009, 3D discrete numerical modelling of ridge keel punch through tests, Cold Regions Science and Technology, vol. 56, no. 1, pp. 18-29.

Selvadurai, A.P.S. 2009, Fragmentation of ice sheets during impact, CMES - Computer Modeling in Engineering and Sciences, vol. 52, no. 3, pp. 259-277.

Tijssens, M.G.A., Sluys, B.L.J. & van der Giessen, E. 2000, Numerical simulation of quasi-brittle fracture using damaging cohesive surfaces, European Journal of Mechanics - A/Solids, vol. 19, no. 5, pp. 761-779.

Timco, G.W. & Weeks, W.F. 2010, A review of the engineering properties of sea ice, Cold Regions Science and Technology, vol. 60, no. 2, pp. 107-129.

Xiao, J. & Jordaan, I.J. 1996, Application of damage mechanics to ice failure in compression, Cold Regions Science and Technology, vol. 24, no. 3, pp. 305-322.

Xu, X.-. & Needleman, A. 1994, Numerical simulations of fast crack growth in brittle solids, Journal of the Mechanics and Physics of Solids, vol. 42, no. 9, pp. 1397-1434.

Zhan, C., Sinha, N.K. & Evgin, E. 1996, A three dimensional anisotropic constitutive model for ductile behaviour of columnar grained sea ice, Acta Materialia, vol. 44, no. 5, pp. 1839-1847.