Dynamic Behavior Of Low Rigidity Frame Under Impact Load

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Abstract: With increasing train speeds and platform overcrowding, passenger safety is becoming an increasing concern. Nabtesco Corporation has developed a platform safety device to allow commuters to safely enter and exit train carriages. CAE was used to confirm the device could be safely operated, even after accidental impact by a train.

Using Abaqus/Explicit, the dynamic impact behavior of the device, consisting of a low rigidity frame structure with an integral brake module, was analyzed and compared with experimental results. Stress fluctuations at several locations on the frame were checked, and the deformation of the soft comb rubber damper was confirmed by high-speed video. Good agreement was obtained on the deformation mode of the rubber damper, where each tooth of the comb realistically transferred the contact to its neighbor throughout the impact. Comparison of stress fluctuations showed the basic deformation of the frame was exactly as simulated throughout the impact. In addition, the intermittent behavior of the frame shown in the simulation seemed to be reasonable, when the effect of braking was taken into account.

Predicted stress values were found to be sensitive to the brake parameters used in the model, and so using actual brake performance should greatly increase the accuracy. However, even when using simple brake parameters the stresses could be predicted to within 50%.

Keywords: Impact, Crashworthiness, Assembly Deformation, Train, Passenger, Rubber

1. Introduction

While sufficient for normal operating conditions, the rigidity of a typical large framed structure composed of section steel is relatively low when subject to unusual loading conditions. So during an unexpected impact, large deformation occurs, and significant stress is momentarily concentrated at the frame connections. In addition, if the structure is complex, it is generally difficult to predict the location and value of the maximum stress.

In the case of static loading, it is only necessary to design within a safety margin, and rigidity can be safely increased by making the frame thicker. However, this might be detrimental to impact load resistance. So in order to estimate the strength of the frame structure under impact loading, the maximum stress was evaluated using Abaqus/Explicit.

Impact testing of a prototype product produced comparable results, thus verifying the accuracy of Abaqus/Explicit.

2. Analytical object

The analytical object described in this paper is installed on railway platforms. It is a moveable footplate that bridges the gap between the train and the platform. Figure 1 illustrates the structure of the analytical object. It is composed of a moving step (green in Figure 1) and slide rails (red) that support and guide the step. The step is fixed on a frame (blue) which bears and slides on the slide rails.

A motor module for driving the step and a brake module to absorb the energy of impact loads are also mounted on the frame. A rubber damper with a comb-type structure is fitted to the front edge of the step, and acts as an impact bumper.

Normally, when the train arrives at the platform and stops the step is extended by the motor drive before the train doors open. After passengers have entered or exited the train, the doors close and the step is retracted before the train leaves.

In this simulation, the scenario of the train accidentally impacting the step in the extended position was analyzed.

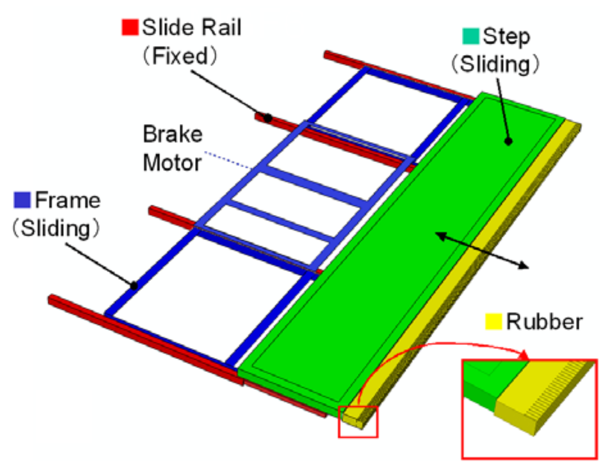


Figure 1. Analytical object structure.

3. Analytical method

3.1 Brake parameters

The reaction force applied by the brake module is defined, in the manufacturer's catalogue, as a constant (independent of velocity). However, the mechanism a friction brake so it is reasonable to assume that the reaction force is subject to both static and dynamic friction effects. So two conditions are used in this simulation; A (constant force) and B (measured variable force), to provide the frictional parameters for the connector element used to model the brake module.

Figure 2 shows the characteristics of the two brake parameters.

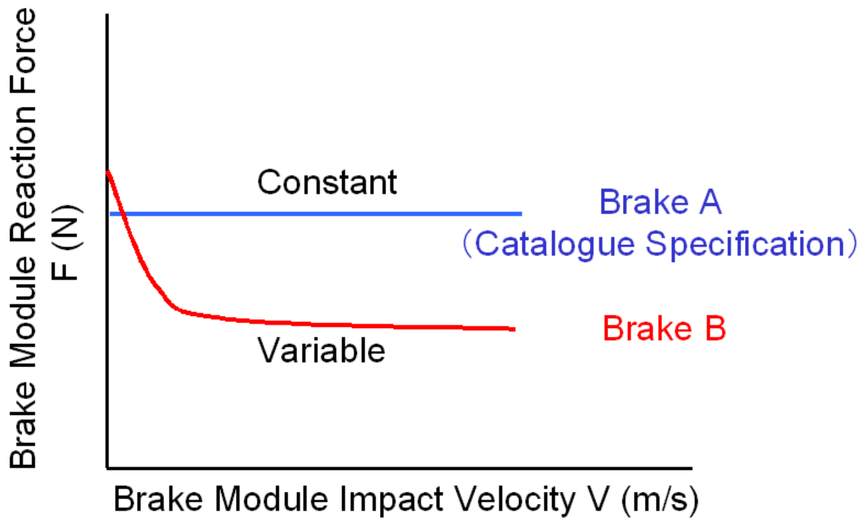


Figure 2. Brake parameters

3.2 Impact conditions

Figure 3 shows the impact conditions.

The front edge of the retractable step is impacted by the front corner of a train carriage. The train carriage is considered to be of perfectly rigid construction. The impact angle is 2.5 degrees, and two impact velocities; 10 km/h and 40 km/h, are considered. Table 1 shows the various combinations of impact velocity and brake parameters considered in four analysis cases.

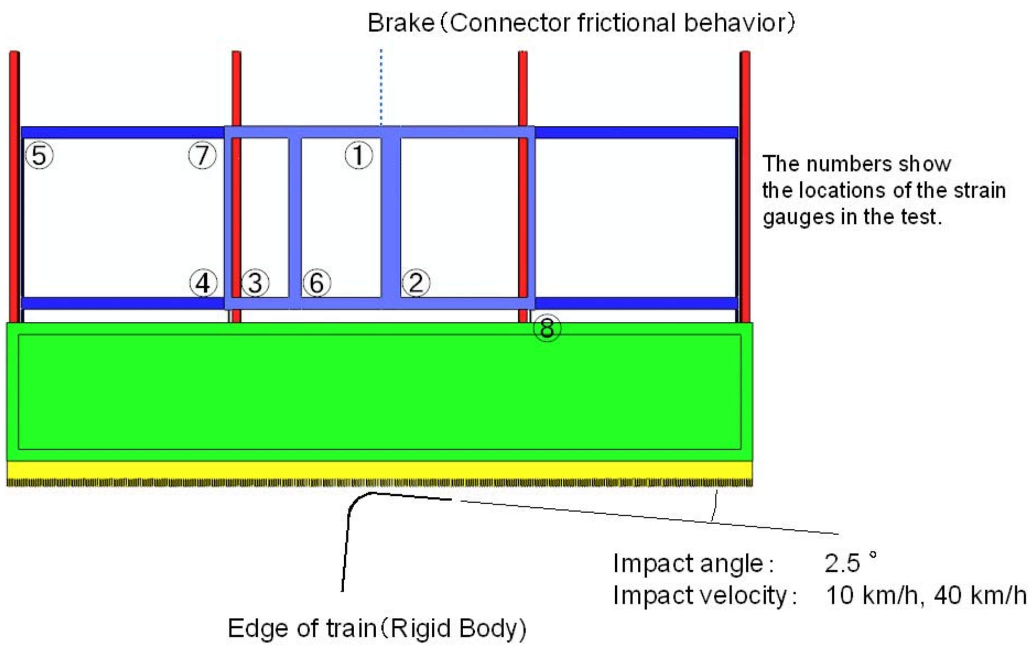


Figure 3. Impact conditions and stress measurement positions.

Table 1. Impact velocity and brake parameters.

Case	Impact velocity (km/h)	Brake parameter
Case10-A	10	Brake A
Case10-B	10	Brake B
Case40-A	40	Brake A
Case40-B	40	Brake B

3.3 Contact conditions

The analysis model includes many contact areas, especially in the slide rails and rubber damper. In addition, many self-contact and sliding contact points occur as the train hits the rubber damper. Therefore, this analysis was carried out using the 'General Contact' function of Abaqus/Explicit.

3.4 Software

Abaqus version 6.7 was used as solver and Abaqus/CAE version 6.7 was used in both the pre and the post-processing.

4. Measurement method

Verification impact tests were carried out to compare with the analysis results, and to assess their accuracy. In the tests, an impactor was raised to a preset height and dropped along a guide rail, giving it a fixed path of motion. It was then made to impact the step on the frame structure under the same conditions as in the analysis. Images of the large deformation of the rubber were captured by high-speed video, and stress values at eight positions, indicated in Figure 3, were measured using strain gauges.

5. Results and discussion

5.1 Comparison of deformation of comb structure rubber damper

The deformation of the rubber damper at the early stages of the impact is illustrated in Figure 4, where images captured by high-speed video are shown alongside stress contour plots from the analysis results.

From the high-speed video images, it is clear that the impactor deforms the soft comb teeth of the rubber damper. In the analysis results, a good agreement was obtained on the deformation mode of the rubber damper, where each tooth of the comb realistically transferred the contact to its neighbor throughout the impact. In addition, the penetration fluctuation of the comb, with corresponding movement of the impacted step and rubber, is in agreement with the video observation.

These results also show that complex sliding self-contacts between each tooth of the comb were calculated successfully and the 'General Contact' feature of Abaqus/Explicit has a high functionality in solving complex contact problems.

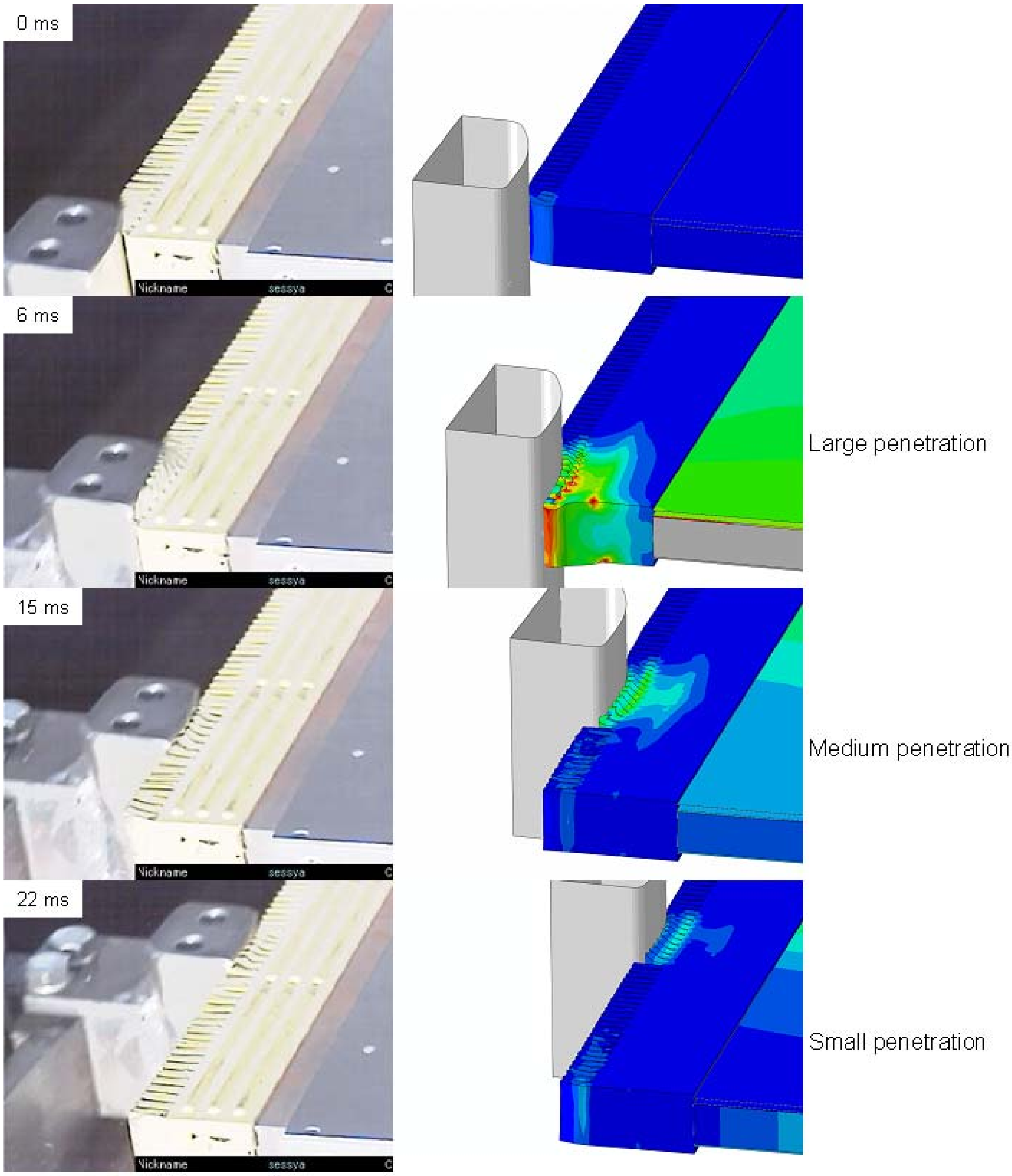


Figure 4. Deformation of rubber damper.

Left: High-speed video images, Right: Mises stress contour analysis results

5.2 Comparison of stress fluctuations on the frame

Table 2 shows a summary of the impact conditions in the test and in the analysis models at 10 km/h and 40 km/h, each using both A and B brake parameters. The table also shows the period and amplitude of the long period stress oscillations and an indication of the relative size of the smaller period oscillations in each case.

Table 2. Summary of impact stress fluctuations in both tests and analyses

Conditions			Result		
Case	Velocity (km/h)	Brake	Long period oscillation		Short period oscillation
			Period (s)	Amplitude (MPa)	
Test	10	-	0.21	75	Large
Case10-A	10	A	0.14	40	Small
Case10-B	10	B	0.22	70	Large
Test	40	-	0.03	85	Large (smaller than 10km/h)
Case40-A	40	A	0.03	80	Small
Case40-B	40	B	0.03	85	Small

Figure 5 and Figure 6 show the stress measurements at eight positions on the frame for both the test and analysis results with both brake parameters at impact velocities 10 km/h and 40 km/h respectively. The stress values in the tests were measured by strain gauges and in the analyses the nodal average stress was found at the node closest to the strain gauge location. The stress fluctuations at the two impact velocities were examined and compared:

- **Impact velocity: 10 km/h**

The results indicate the following features.

i. Two kinds of oscillations were observed. The first is three long period oscillations of large amplitude; the second is several short period oscillations of small amplitude superimposed on the long period oscillations.

ii. High tensile stresses occur at positions 2, 4, 7, and high compressive stresses occur at positions 3, 5, 6. The maximum stress is about 75 MPa at position 4.

The analysis results show a large difference in behavior between brake parameters A and B. In the case of constant brake force (Case10-A), although three long period oscillations exist, their period is slightly shorter and their amplitude is about half that in Case 10-B. The short period oscillations are not clearly defined. On the other hand, when the velocity dependent brake force is considered (Case10-B), three long period oscillations are clearly defined, and their period and maximum stress are in good agreement with the test results. In addition, the short period oscillations are clearly defined.

Regardless of the brake parameter used, the position and the sign (tensile or compressive) of the large stresses are in accord with the test results.

It is clear that the stresses remain after the third long period oscillations and this is because at this low impact velocity the impactor completely stopped while still in contact with the frame in a deformed position.

- **Impact velocity: 40 km/h**

Comparison of the test results and analysis results indicates the same tendencies as at the 10 km/h impact velocity cases. The notable difference is that the long period oscillations are not as clear and the second oscillation is remarkably low in amplitude. In addition, the influence of the brake parameters does not appear as significant. However, the maximum stress and the length of the first long period oscillation is a good agreement with the test results.

In the test results, the short period oscillations at 40 km/h impact velocity are smaller than those at 10 km/h impact velocity. The probable explanation for this is that some resonance occurred at 10 km/h impact velocity and the impact behavior was dominated by smaller, local deformation of the frame members, whereas at 40 km/h the behavior exhibited larger, global deformation.

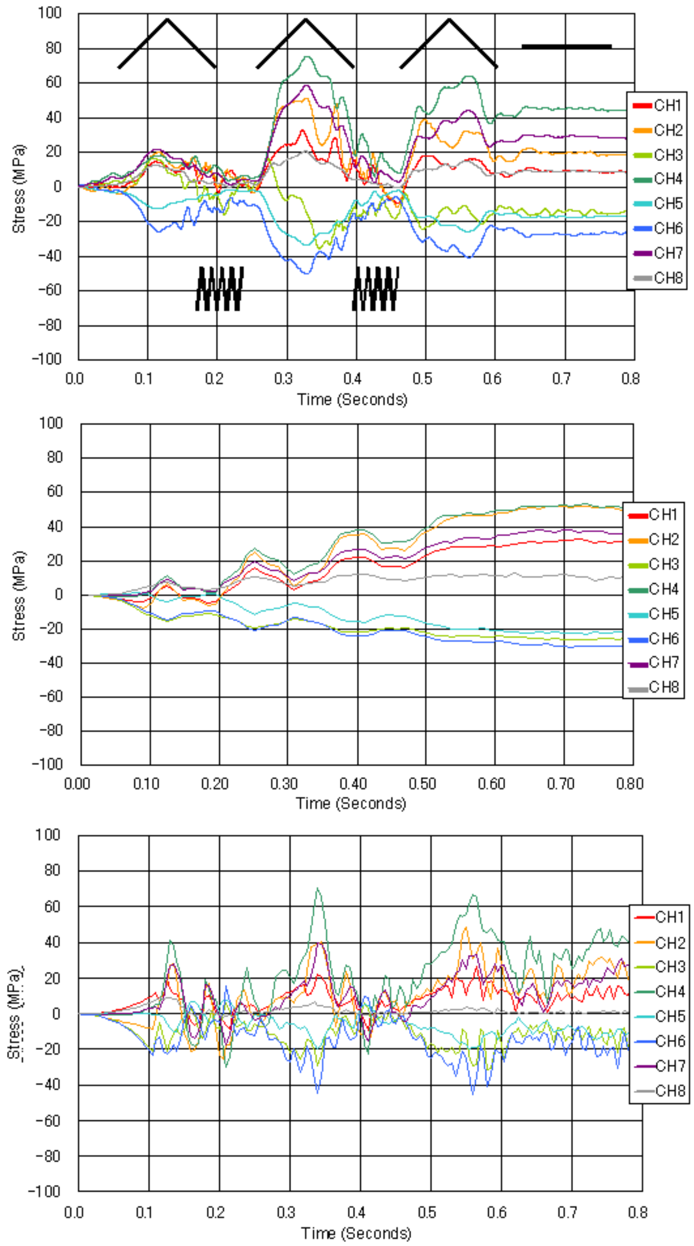


Figure 5. Stress fluctuations at 10 km/h impact velocity.

Top: Test, Middle: Case10-A analysis, Bottom: Case10-B analysis

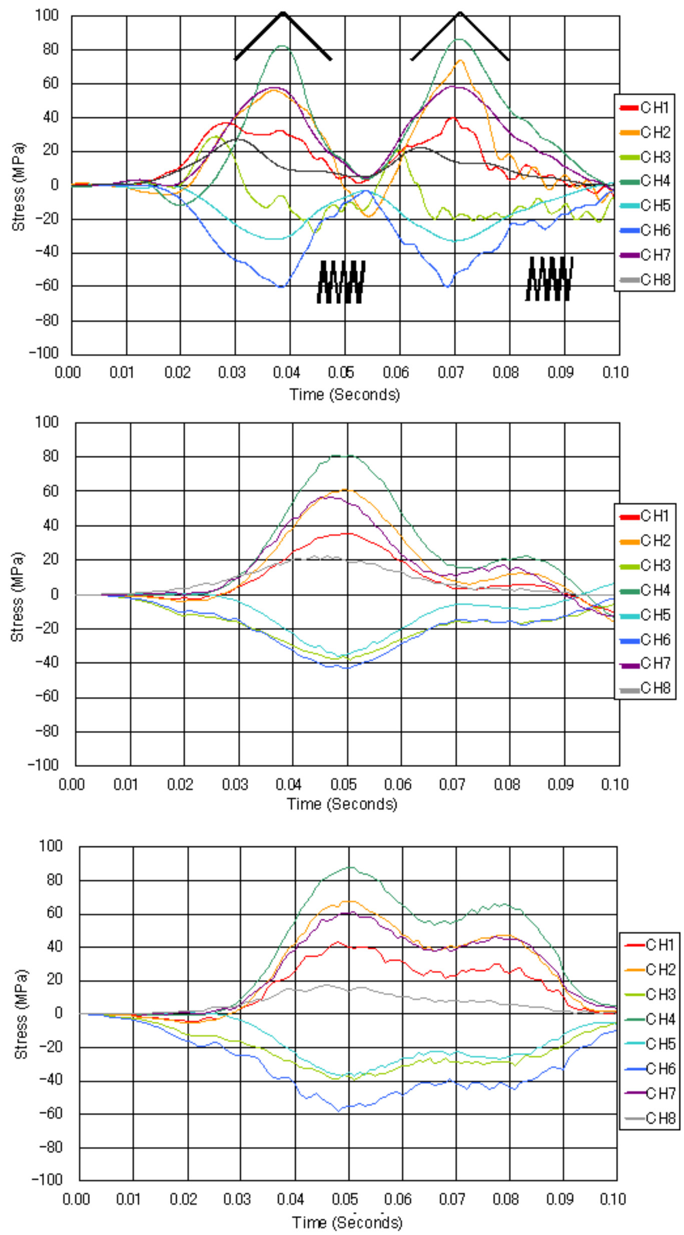


Figure 6. Stress fluctuations at 40 km/h impact velocity.

Top: Test, Middle: Case40-A analysis, Bottom: Case40-B analysis

5.3 Deformation mode of the frame

The frame deformation at the peak and valley of the long period oscillations in the stress fluctuations are shown in Figure 7-a for Case10-B. The stress at the contact point indicates that the impactor hits the frame strongly during the oscillation peaks, and it impacts the frame weakly during the valleys. This result follows from the intermittent dynamic behavior of the frame, which is caused by the impactor moving the frame, the frame separating from the impactor, the energy of the frame being absorbed by the brake, and the impact re-occurring as the frame decelerates. Figure 7-b shows the deformation of the first frame with a larger displacement magnification factor. This figure shows that during the collision the impactor pushes the frame to the side causing buckling.

5.4 Overall validity of analysis

- **Deformation**

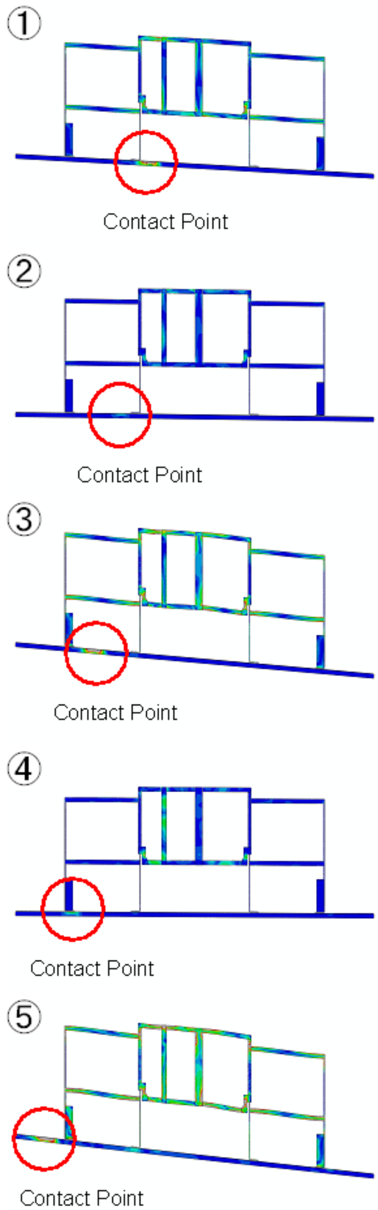
The deformation of the soft comb structure rubber damper is in good agreement with the high-speed video observation. This suggests that the contact between the impactor and the rubber, and even the sliding self-contact of each of the comb teeth was successfully analyzed. Therefore, a good degree of accuracy is achieved for the impact of the soft rubber damper.

It is, however, impractical to observe in detail the overall deformation of the frame directly, and so difficult to verify. However, comparison of the stress fluctuations shows that the positions and sign of the high stress, and the length of the large period oscillation were exactly simulated. In addition, the intermittent dynamic behavior of the frame seems to be reasonable. Therefore, the overall deformation behavior of the frame can be also calculated to a relatively high degree of accuracy.

- **Stress on the frame**

In each analysis result, a long period stress oscillation was observed and the influence of the brake parameters was confirmed. It is thought that the influence of the brake parameters at 10 km/h impact is larger than that at 40 km/h because during the 10 km/h impact the velocity dependent brake force varies more that at 40 km/h, where the velocity remains high enough during the impact interval to keep the brake force in the relatively constant portion of its behavior. (Figure 2)

Even if the constant brake parameter is used, as in the manufacturer’s catalog specification, the maximum stress on the frame can be calculated to within about 50% of the measured value. Considering this result, Abaqus/Explicit can be regarded as a useful tool for designing low rigidity frame structures that require strength evaluation under impact conditions.



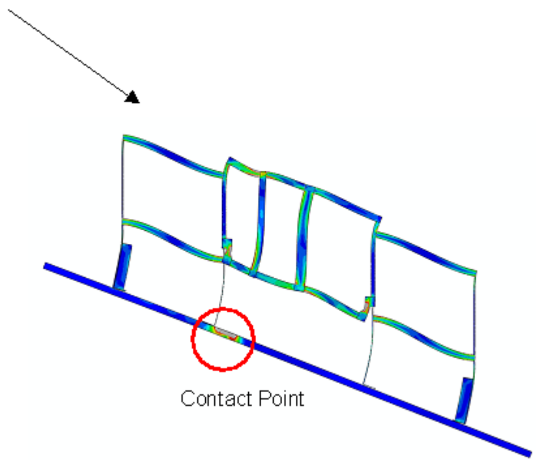


Figure 7-b. Displacement magnification factor 350

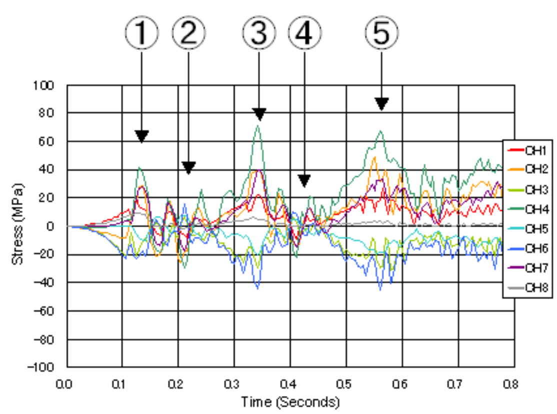


Figure 7-a. Frame deformation and stress fluctuations.

(Mises stress contours, displacement magnification factor 25)

6. Conclusions

The strength of the low rigidity frame was estimated using Abaqus/Explicit, and the analysis results were compared with verification tests carried out on a trail product. The experimental verification indicates the following conclusions.

i. A good agreement was obtained on the dynamic behavior of the low rigidity structure including the soft comb structure rubber damper.
ii. In the stress estimate, even using the manufacture's catalog specification of a constant brake parameter, the maximum stress on the frame can be calculated to about 50% of the measured value.
iii. The brake parameters and the impact velocity greatly influence the stress fluctuation, and the analysis accuracy was improved using brake parameter B, derived from accurate measurement of the actual dynamic performance of the brake.
iv. It is concluded that Abaqus/Explicit can be a useful tool for designing low rigidity frame structures that require strength evaluation under impact conditions.

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