Highly-Reliable CAE Analysis Approach - Application in Automotive Bolt Analysis -

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Abstract: - In this paper, the authors propose a model for a highly-reliable CAE analysis approach, which is intended to contribute to the regeneration of development and design. This model has been applied with significant results in making proposals for bolt tightening behavior analysis, which continues to be an area of concern.

Key-Words: development and design, robust design, highly-reliable CAE analysis approach, bolt tightening, stress analysis, nut flange analysis

1 INTRODUCTION

In order to survive in the "worldwide quality competition", Japan's automotive industry must reform its development and design processes, and establish a new model of Japanese management technology capable of achieving simultaneous quality, cost, and delivery (QCD).

Automotive development in the past has involved repetitive post-development experimenting, prototyping, and evaluation based mainly on problem-detection and kaizen. Nowadays, in some development processes, body prototypes are not produced and CAE and Simultaneous Engineering (SE) are applied in the early stages of development instead, resulting in a greatly shortened vehicle development period [1] [2].

For this reason, it is considered necessary to change over from the conventional confirmation of actual products for improvement to a predictive evaluation-based approach employing digital engineering methods such as Computer-Aided Engineering (CAE) in order to achieve extremely short development periods [3].

Thus, in this study, the authors propose a model for a highly-reliable CAE analysis approach, which is intended to contribute to the regeneration of development and design. In order to confirm the validity of this approach, it has been applied with significant results in automotive nut flange analysis, which continues to be an area of concern.

2 ISSUES IN APPLYING CAE IN THE REGENERATION OF DEVELOPMENT AND DESIGN

In order to reform processes to a predictive evaluation-based approach, the authors have identified issues that arise when applying CAE, and organized the main points in figure 1 from the perspective of achieving simultaneous QCD [3].

Fig. 1 Issues in applying CAE in regeneration of development and design

As shown in the figure, in order to achieve simultaneous QCD, the application of CAE analysis technology must be improved. This involves understanding the mechanisms behind the main technical problems and accurately representing them...
in numerical calculations (simulation). More specifically, it is essential to enhance the level of CAE analysis to enable the results of actual experiments to be reproduced reliably and accurately.

3 EFFECTIVENESS OF THE TECHNOLOGICAL ELEMENT MODEL FOR HIGHLY-RELIABLE CAE SOFTWARE

Figure 2 shows a model representing the technological elements required for effectively applying highly-reliable CAE software in development and design processes, based on previous findings and empirical research [3]. As shown, in order to create intelligent CAE analysis software that assures high quality without relying on actual testing, it is vital to have a thorough understanding of the following technical elements: (1) problem setting (checking problem with actual product), (2) algorithm (calculation method), (3) modeling (numerical calculations, model application), (4) theory (establishing problem-solving theories), and (5) calculation technology (selecting a calculator).

The figure shows that there is a broad range of options available when selecting technical elements for general CAE analysis. However, from the standpoint of implementing CAE as a problem-solving method on a working level, the sheer number and wide selection of these elemental technologies is not sufficient. This is because CAE is thought to be a process consisting of multiple elemental technologies [4] [5].

When conducting CAE analysis, it is first necessary to (1) set the problem to be solved, and (2) model the problem using a suitable algorithm. Next, (3) although a calculator will be used to analyze the model, analysis software must be used (an algorithm must be applied) to enable the model to be reproduced. Then, (4) a theory must be applied to determine the algorithm’s suitability, application range, performance, and expected accuracy. (5) Of course, the success of the CAE analysis depends largely on the technology related to the calculator itself, which will be used to reproduce the algorithm.

4 HIGHLY-RELIABLE CAE ANALYSIS APPROACH

The authors propose the highly-reliable CAE analysis approach as a methodology for enabling the simultaneous achievement of QCD.

Functional failures are a recurring cause of market claims in automotive development and design, making it necessary to clarify relevant technical issues such as the reasons and mechanisms by which such failures occur. This should be done according to the following steps.

Step 1: Test actual products demonstrating the failure mechanisms and clarify the dynamic behavior of the problem at the time of occurrence using visualization technology.

Step 2: Clarify the structure of the problem (mechanism) and accurately model the causal relationships. It is important to collaborate with internal and external specialists to pool knowledge, and apply the latest SQC methods to analyze the causal relationships uncovered in order to estimate the mechanisms of the failure. In order to accurately analyze the failure and its causes, it is necessary to uncover any underlying factors that were not evident from previous findings and may have been overlooked.
A logical reasoning process must be applied to demonstrate the mechanisms of the failure, employing tools and principles such as the seven New SQ tools (N7), Statistical Quality Control (SQC), Reliable Engineering (RE), Multivariate Analysis (MA), and Design of Experiments (DE).

Step 3: Consolidate the findings and apply numerical simulation to create a two-dimensional model integrated on a qualitative level where the visualization produced through actual testing can be reproduced. When creating this two-dimensional model, it is necessary to conduct tests to produce a model (qualitative modeling) of the causal relationships involved in undefined failure mechanisms. Precise calculation methods, analysis models and algorithms must be properly selected in order to clarify boundary conditions and contact situations and enable highly accurate numerical simulation. It is essential to use such tools to minimize discrepancies between actual testing and CAE absolute evaluation. The findings from such analysis should then be used for more detailed three-dimensional analysis.

Step 4: Conduct accurate testing of actual products based on the findings from step 3 to gain a more explicit understanding of the failure mechanisms. Consolidate the findings from the processes involved and conduct numerical simulation with a high level of credibility to identify the design factors and enable the prediction and control of absolute values.

Step 5: For predictive evaluation CAE analysis, identify the primary factors from the results of the numerical simulation in step 4 to be used for prediction and evaluation. The new findings obtained, design concepts, and formulation models should be shared and disseminated to enable the rapid improvement of robust designs.

Utilizing models with a higher level of analytic accuracy enables an advance from relative evaluation to absolute evaluation of analysis results in the actual development process. The authors believe that this will lead to the future establishment of design frameworks involving predictive evaluation.

5 APPLICATION EXAMPLE: AUTOMOTIVE NUT FLANGE ANALYSIS THROUGH ACTUAL EXPERIMENTS AND CAE

5.1 Bolt Tightening Experiments

Bolt-tightening experiments were conducted using flanged hexagonal bolts and nuts. First, static tests were conducted in order to estimate the vibration load to be used in the vibration test. A load was applied to bolt fasteners tightened with forces of 20 kN, 35 kN, and 50 kN and a tester was used to measure the load when the flange slip suddenly increased. An upper
vibration jig was used to apply an external force perpendicular to the axis to cause vibration displacement. The tightening load on the bolt was measured to determine changes in the tightening load corresponding to the displacement. The tester was then used to apply vibration loads at ±60%, ±75%, and ±90% of the static extraction loads measured in the static tests. This was used to determine the occurrence of bolt looseness by repeatedly causing flange slip. Changes in the bolt tightening loads and displacement between the bolt and the tester corresponding to the number of repetitions were measured.

5.2 Numerical Simulation
The authors conducted two-dimensional bolt tightening analysis using numerical simulation to create a two-dimensional axial symmetry model in order to gain an overall understanding of the boundary conditions, integrity of the model, and contact relations for CAE bolt analysis. Analysis was conducted on the basis that a thread is generally a helical structure and can be thought of as an axisymmetrical crest of a uniform height wrapped around a central core. The results indicate a high degree of stress on (1) the boundary face between the substrate and the nut, and (2) the tip of the threaded portion.

In the next step, a three-dimensional model was analyzed according to the finite element method, taking into account the helical structure of the threaded portion. The boundary conditions were determined and the axial force and torque were calculated in order to enhance the accuracy of the bolt vibration test simulation results. The stress on the threaded portion of the bolt and the nut flange was then determined in order to compare the values with the stress distribution shown by the results of the bolt vibration test simulation. The stress on the threaded portion of the bolt and the nut flange was then determined in order to compare the values with the stress distribution shown by the results of the bolt vibration test simulation. In the three-dimensional finite element model, the area around the bolt and nut and the contact sections are represented by a fine mesh compared to the 2D finite element model. Analysis was conducted according to the following steps. (1) The parts to be clamped (2 substrates) were placed between the bolt and the nut. (2) Axial force was applied to the bolt and the stress distribution during contact was obtained. Then, the edge of the lower substrate was secured, and an upward perpendicular force (axial) was applied to the upper substrate. (3) The pressure on the contact faces (bolt/nut bearing surfaces and between the bolt crest and nut) was obtained.

5.2.1 Bolt Tightening Analysis
Figure 4 is a Von Mises stress diagram (cross-section) showing the results of analysis when axial force was applied to the upper substrate in a perpendicular direction. The contact portion of the threaded section is enlarged.

The figure shows a higher Von Mises stress value for the lower part of the threaded section than the upper part. It is clear that uneven stress was occurring on the nut flange. Such uneven stress on the nut flange leads to a reduction in contact force, causing flange slip. By comparing the stress distribution results with the results of the vibration test analysis, it was possible to confirm an increased unevenness in the stress distribution on the nut flange corresponding to the external perpendicular axial force, thereby discovering the cause of the flange slip.

5.2.2 Stress Analysis for Contact Surface Between Nut Flange and Substrate
Figure 5 shows the results of analysis when axial force was applied to the upper substrate in a perpendicular direction, and axial extraction force was applied to the substrate on the nut side.

The figure shows that the unevenness of the stress on the nut flange increased compared to the results of the bolt tightening analysis. More specifically, this means that substantial localized stress occurred on the start point of the nut's helical structure. When a load is applied to the substrate, the unevenness of the stress on the nut's flange increases. Further, the difference widens between sections where stress is substantial and sections where it is minimal. These results
indicate that reducing the contact force on the flange contact section leads to flange slip.

5.3 Verification Using Three-Dimensional CAE Analysis

The accuracy of the CAE analysis results was verified by comparing them with measurements obtained by measuring the pressure on the contact faces of the nut and the substrates using pressure measurement film, for which Prescale was used. Patches of color appear on the film where pressure is applied, and the color density varies according to the level of pressure. Figure 6 shows the results of the pressure measurements using Prescale, while Figure 7 shows the results of the CAE simulation.

Comparisons were made concerning the average pressure on the flange, and four sections including the area around the start point of the nut's helical structure. In the figures, A1 indicates the area around the start point of the nut's helical structure. This area was selected due to the significant stress values obtained from the CAE simulation, making it a possible factor in flange slip. The three other points chosen were laterally and vertically opposite. The maximum, minimum, and average stress values in each section show that significant pressure occurs on the nut flange around the start point of the nut's helical structure, and a similar distribution is found when compared with the results of the CAE simulation. Discrepancies were found in the values obtained due to deformation, wear, and unevenness in the contact sections after the bolt tightening tests. However, it was possible to determine the actual stress distribution on the nut flange and reproduce it through simulation, which would not normally be possible.

6 CONCLUSION

In this paper, the authors proposed a model for a highly-reliable CAE analysis approach, which is intended to contribute to the regeneration of development and design by enabling the changeover from the conventional confirmation of actual products for improvement to a predictive evaluation-based approach employing CAE analysis. This model has been applied with significant results in visualizing the detailed stress distribution on nut flanges through simulation, and its effectiveness has been verified by applying it to the analysis of nut flanges for automotive bolts.

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