American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-10, pp-178-187
www.ajer.org

Research Paper Open Access

Developing a highly reliable cae analysis model of the mechanisms that cause bolt loosening in automobiles

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ABSTRACT : *In this study, we developed a highly reliable CAE analysis model of the mechanisms that cause loosening of bolt fasteners, which has been a bottleneck in automobile development and design, using a technical element model for highly accurate CAE that we had previously developed, and verified its validity. Specifically, drawing on knowledge gained from our clarification of the mechanisms that cause loosening of bolt fasteners using actual machine tests, we conducted an accelerated bench test consisting of a three-dimensional vibration load test of the loosening of bolt fasteners used in mounts and rear suspension arms, where interviews with personnel at an automaker indicated loosening was most pronounced, and reproduced actual machine tests with CAE analysis based on a technical element model for highly accurate CAE analysis. Based on these results, we were able to reproduce dynamic behavior in which larger screw pitches (lead angles) lead to greater non-uniformity of surface pressure, particularly around the nut seating surface, causing loosening to occur in areas with the lowest surface pressure. Furthermore, we implemented highly accurate CAE analysis with no error (gap) compared to actual machine tests.*

Keywords -*CAE, Bolt fastener, Reliable*

I. INTRODUCTION

Japan's automotive industry enjoys a position of international prominence. However, since the industry began to address the problem of recalls following greater social awareness of the issue in recent years, there has been a trend toward increases in both the number of recalls and the number of vehicles involved. Serious quality problems such as this threaten the very social status of the companies involved and could end up compromising the status of the Japanese manufacturing industry as a whole, which has traditionally competed successfully with counterparts in other countries. Consequently, it has become a key for companies to pursue measures to address quality defects and to establish systems for preventing such defects.

Moreover, recent diversification of consumer needs is driving the industry toward a super-fast development and design cycle, and it will be difficult for automakers to survive as companies if they are unable to outcompete their rivals, both domestically and overseas. For these reasons, automakers are seeking to put in place development and design systems that deliver high quality and short lead times and using computer-aided engineering (CAE) to pursue concurrent engineering. In recent years, the industry has sought highly accurate CAE analysis that yields results that do not diverge from actual machine test results, but the state of the art in such analysis has stopped at relative evaluation, which does not allow companies to perform predictive evaluation. The reason for this impediment lies in differences in how companies developing CAE analysis software and their customers in the manufacturing industry use that software.

Against this backdrop, this paper develops a highly reliable CAE analysis model that facilitates a predictive evaluation-oriented CAE design system. We conducted a two-dimensional CAE analysis to determine test characteristics values for actual machine tests and to set three-dimensional CAE analysis parameters drawing on information gained from previous research[1-8]. Next, we conducted actual machine tests and a three-dimensional CAE analysis. By applying this model so that we could conduct a three-dimensional analysis after setting only a minimum number of test parameters, we were able to boost the accuracy of the prediction and evaluation processes.

To verify the validity of this model, and to provide an example application, we conducted a bolt loosening vibration test using actual vehicle parts and a CAE analysis, focusing on clarifying the mechanisms that cause loosening of bolts. Specifically, we focused on comparing bolts and nuts with different pitches and studied the causes that lead to bolt loosening by comparing the drop in axial force during bolt fastening and assessing the stress distribution at areas of contact on the nut seating surface [9].

II. HIGHLY ACCURATE CAE ANALYSIS MODEL

In this section, we will focus on the loosening of bolt fasteners and offer a five-step approach to implementing highly accurate CAE analysis in the development and design process, as summarized inFig.1.

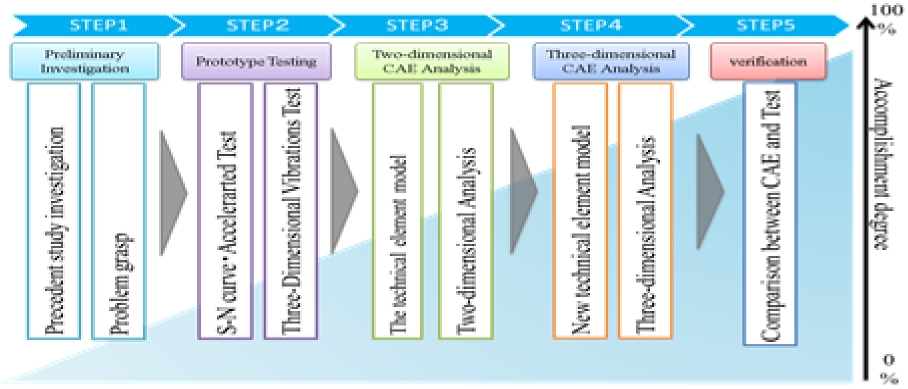

Fig.1Highly Accurate CAE Analysis Model

2.1 Preliminary Investigation

In order to solve the technical problems that lie behind market complaints (cases where manufacturers are unable to reduce the incidence of functional failures, which is an area of concern in automobile development and design) by determining, for example, why failures occur and the mechanisms that are responsible for them, it is important that step 1 be to engage in cooperative creative activities that bring together the knowledge of in-house and outside experts. It is also important to use the latest techniques of statistical science to investigate and analyze convergent causal relationships and conduct a detailed analysis of the phenomenon in question in order to deduce the failure mechanism in step 1.

2.2 Prototype Testing

In order to visualize the phenomenon in question, it is necessary to visualize the dynamic behavior that accompanies the occurrence of the problem using actual machines and tests. In this step 2, we search for latent factors that have remained unknown or overlooked using techniques such as N7 (new seven QC tools), SQC (Statistical Quality Control), RE (a reliability technique), MA (multivariate analysis), and DE (experimental design) to analyze the failure and its principal causes in a precise manner.

In this way, the failure mechanism is verified by means of a logical thought process. We also analyze the mechanism based on the phenomena that were visualized through actual machine tests. Then by conducting other tests, we identify issues that could not be fully understood by means of the visualization tests. These issues are identified through the three-dimensional CAE analysis carried out in Step 3.

2.3 Two-dimensional CAE Analysis

In this step 3, we carry out two-dimensional CAE analysis by modeling the phenomenon being studied using CAD based on the parameters obtained during the actual machine tests. The objective is to assess characteristics values and boundary conditions for the three-dimensional CAE analysis and to predict its results.

2.4 Three-dimensional CAE Analysis

Based on the two-dimensional CAE analysis, we then establish a technical element model for three-dimensional CAE analysis and devise an analysis model. In particular, we develop a three-dimensional model that achieves consistency at a qualitative level by using three-dimensional CAD. At this step 4, it will be necessary to conduct actual machine tests that model (qualitatively) the causal relationship characterizing the unexplained mechanism, and it becomes important to select precise calculation techniques, analysis models, and algorithms in order to clearly identify boundary conditions and contact states and conduct a highly accurate numerical simulation.

In addition, we create a technical element model, which is the most important approach model in order to explicate technical problems. Through this process, it is extremely important to shrink the gap by absolute value evaluation of actual machine and tests and CAE results.

In highly reliable CAE analysis, a thorough battery of actual machine tests is performed based on the information gained from the logical thought process described above in order to adequately clarify implicit knowledge about the failure mechanism. Then we integrate the information gained from these work processes to conduct a highly reliable numerical simulation (quantitative modeling) enabling prediction and control of absolute values.

2.5 Verification

In this step 5, we conduct a comparative verification and evaluation of actual machine test results and three-dimensional CAE analysis results. The benefits of this approach model are apparent in its ability to deliver enough accuracy to keep the error within 3%. Additionally, by using a model that increases the accuracy of the analysis, it is possible to transition from relative evaluation to absolute evaluation in the use of analysis results in development. We believe that this transition will lead to the establishment of a prediction- and evaluation-based design system.

III. EXAMPLE APPLICATION-ANALYSIS OF THE MECHANISMS THAT CAUSE BOLT FASTENER LOOSENING IN BOLT-FASTENED PARTS IN MOUNTS AND REAR SUSPENSION ARMS-

Our purpose was to clarify behavior in terms of stress distribution on nut seating surfaces, which is an important problem when using bolt fastening, and to search for behavior consisting of a reduction in axial force caused by simultaneous vibration from the three axial directions. We focused our tests on the mount and rear suspension arms, both of which are automotive components, and set out to visualize the mechanisms that cause bolt loosening in those parts. To do so, we used fatigue testing (three-dimensional vibration testing) of bolt fasteners to assess the stress distribution on the nut seating surface and the behavior of axial force reduction using time sequences of data.

3.1 Bolts and Nuts Used

We chose M12 10T flanged hexagonal bolts and nuts with three different pitches (0.50 mm, 1.25 mm, 1.75 mm) for testing. Since the bolts and nuts would be used in the rear suspension, we used the largest and smallest pitches of 0.50 mm (Fig. 2) and 1.75 mm (Fig. 4) that could be manufactured in compliance with the JIS standard for bolts and nuts with a pitch of 1.25 mm (Fig. 3).

Fig.2 Pitch 0.50mm

Fig.3 Pitch 1.25mm

Fig.4 Pitch 1.75mm

3.2 Used Equipment

Concerning the equipment used in our tests (Fig. 5), we reproduced a working chassis designed to simulate bench testing of an actual vehicle. Furthermore, the mount and suspension arm shown in Fig. 6 and Fig. 7 were the automotive parts most prone to loosening according to interviews at YaeiAutomobileMaintenance Factory. We combined these parts to conduct tests to subject the bolt fasteners to vibrations in three dimensions.

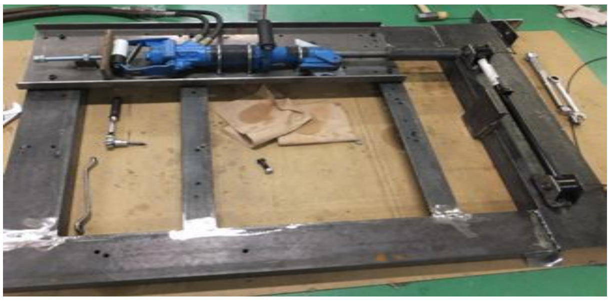

Fig. 5Vibration-Testing Machine

Fig. 6Rigid Part

Fig. 7 Rear Suspension

3.3 Bolt Fastening Test

Our objective in actual machine tests was to ascertain the axial force extraction fastening load at which sliding of the seating surface occurs and to identify the mechanisms that cause bolt loosening due to three-dimensional vibration. First, we determined the stress amplitude value to use in accelerated testing. Furthermore, we identified the loosening mechanism by applying that value to the bolts, nuts, equipment, and parts being used.

3.3.1 Accelerated Test

We used an accelerated test as the first actual machine test. In an accelerated test, it is possible to trigger a failure in a shorter amount of time (smaller number of cycles) than usual by applying a large stress amplitude. Our accelerated stress procedure consisted of creating an S-N curve based on the results of past tests conducted by the Amasaka-Laboratory and then using Miner's rule to calculate the acceleration coefficient [3, 6, 7]. We then conducted the accelerated test.
(a)S-N Curve

Fig. 8 illustrates the results of plotting a curve consisting of the number of vibration cycles (N) at which bolt loosening occurred in past tests versus the stress amplitude (S) at that point in time.

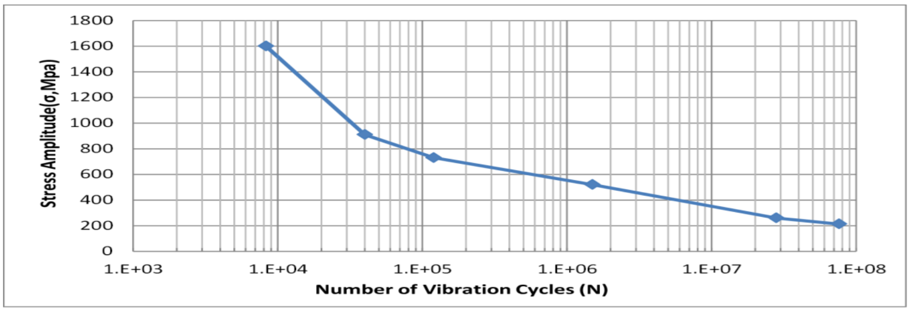

Fig. 8S-N Curve

(b) Miner's rule

$$\sum_{n=1}^{\infty}\left(\frac{n_i}{N_i}\right)=1 \qquad (1)$$

$$N_i * S^{\alpha} = \beta \qquad (2)$$

The approach of Miner's rule can be expressed by (1) above. The stress amplitude (S), repeat cycles (N), and stress cycles (n) at the maximum and minimum value points from the S-N curve calculated in (a) are substituted into (2) to calculate the acceleration coefficient (α). Then the damage-specific coefficient (β) is calculated from the calculated acceleration coefficient (α) and (2), and as a result the stress amplitude (S) is calculated. The stress amplitude value calculated here was used as the stress amplitude in this paper's actual machine tests.

(c)Determining the amplitude output device

Next, we study vibration generators capable of outputting the stress amplitude value calculated using the S-N curve in (a) and Miner's rule in (b). We looked at vibration motors and jackhammers manufactured by EXEN Corp. and Maruzen Co., Ltd., and ultimately chose to use the BH-16 (Fig. 9) as the vibration output device for our actual machine tests.

Fig. 9Jackhammer Manufactured by Maruzen Co., Ltd.

3.3.2 Three-Dimensional Vibrations Test

First, to estimate the vibration load to use in the vibration test, we applied a fastening load of 12 kN to the bolt fasteners in a static test to measure the tester load at which sliding of the seating surface increased abruptly. Specifically, we applied a series of varying three-dimensional vibrations to the fixture holding the mount and rear suspension arm in place (Fig. 5).

Then, we applied vibrations to the tester at a vibration load equivalent to ±20% of the static extraction load. At this point, we ascertained the phenomenon by which bolt loosening occurs due to repeated sliding of the seating surface. In this test, we measured the displacement between the bolt and tester and the trend in the bolt axial force extraction load relative to the number of repetitions. The results are summarized in Fig. 10 and Fig. 11 below.

In both figures, the 1.25 mm pitch bolts are subjected to vibrations under the same test conditions, but only the suspension arm (Fig. 12) is fastened at both ends by two bolts. The line graph shows the mount results in yellow, the area of the suspension to which external stress was applied (red circle) in red, and the fixed part on the opposite side (blue circle) in blue. Both show a reduction in axial force, but we found that for the suspension arm, the area shown by the red circle loosened first, and then the area shown by the blue circle loosened in response.

Based on the large reduction in axial force at the mount, we also found a link with suspension arm hazard and the manner in which the bolts loosen.

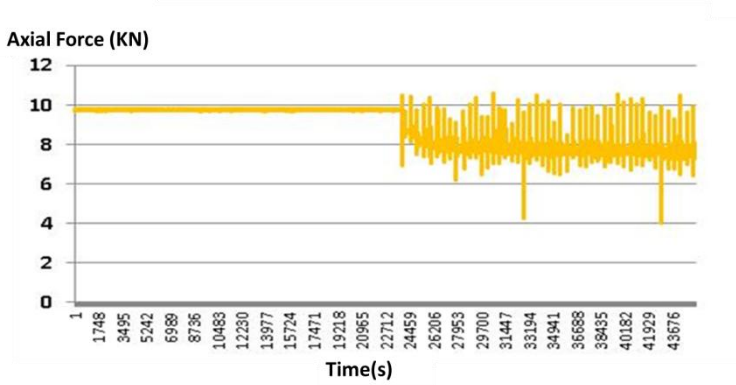

Fig. 10Result of Rigid Par

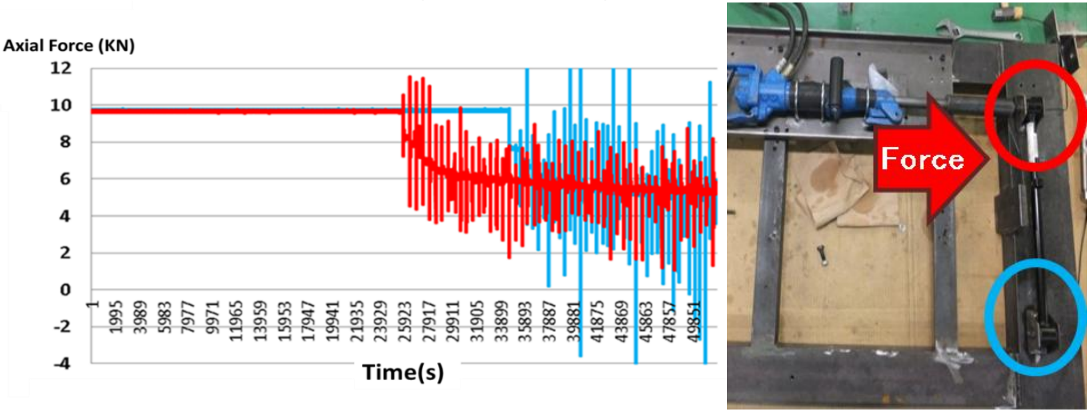

Fig. 11Result of Rear Suspension

3.4 Two-Dimensional Analysis

In this section, we describe how we created a technical element model expressing the elements shown in Fig. 12 below in order to ascertain the stress behavior inside the bolt and to improve the accuracy of our three-dimensional CAE analysis. To achieve those objectives, it is necessary to carry out a highly accurate CAE analysis without any inadequacies in terms of modeling, algorithms, theory, or computer technology.

In modeling, the model’s material properties must be uniquely selected in the form of a material constitutive model. These properties are then assigned as quantitative values for the constitutive model that defines the material.

In terms of theory, the coefficients of friction serve as important elements. In this case, we assigned the coefficients of friction for the thread and seating surface as quantitative values based on test results. In terms of the calculation technique, we opted to use the penalty method based on consideration of the balance between calculation time and accuracy.

Based on the above considerations, we conducted a finite element analysis using a two-dimensional model taking into account the thread’s helical structure and contact.

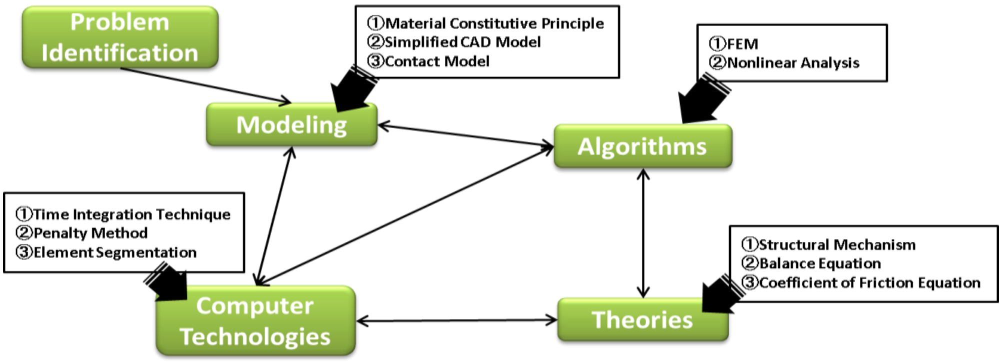

Fig. 12Two-Dimensional Technical Element Model

3.4.1 Result of Two-dimensional Analysis

Fig. 13 and Fig. 14 illustrate the results of a numerical simulation that applied external force from the left side of thefigures to the 0.50 mm and 1.75 mm pitch bolts, respectively, using the same boundary conditions as the actual machine tests. The contours indicate stress, with stress values increasing as the colors change from blue to red. These figures indicate that while the stress spread throughout the bolt with the short 0.50 mm pitch, it was concentrated in the area indicated by the red circle in the bolt with the longer 1.75 mm pitch.

Furthermore, based on the numerical stress distribution, it can be predicted that the 1.75 mm pitch bolt would loosen more readily due to the high load on the thread helix and nut seating surface. Based on this analysis, we were able to estimate such information as the coefficient of friction for each pitch, the element segmentation method, and contact condition, as detailed in Table 1. We then conducted a three-dimensional analysis using the conditions and characteristics values obtained in this step.

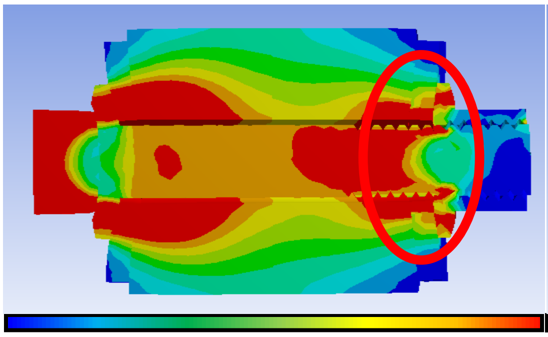

Fig. 13 Result of 0.50mm Pitch

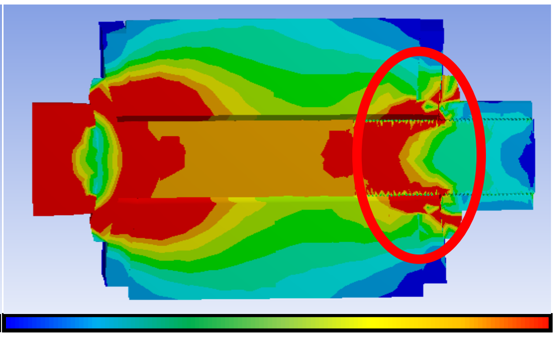

Fig. 14 Result of 1.75mm Pitch

Table 1Information Gained from the Two-dimensional Analysis

Pitch	COF	Element Model	Contact Condition	MAX Stress(Mpa)
0.50mm	0.08691	Equilateral Triangle	Lagrange Multipliers Method	84
1.25mm	0.19398	Equilateral Triangle	Lagrange Multipliers Method	106
1.75mm	0.30420	Equilateral Triangle	Lagrange Multipliers Method	146

3.5 Three-Dimensional Analysis

We created a new technical element model, illustrated in Fig. 15, in order to facilitate a highly accurate three-dimensional analysis. Our objectives with this model were to (1) ascertain the contact surface pressure on the nut seating surface and (2) assess the phenomenon of reduced axial force. To achieve these objectives, highly accurate CAE analysis can be performed by implementing modeling, algorithms, theory, and computer technology without any inadequacies. The model diagram expresses the relationships between the elemental technologies of (1) problem identification, (2) modeling, (3) algorithms, (4) theory, and (5) computer technology.

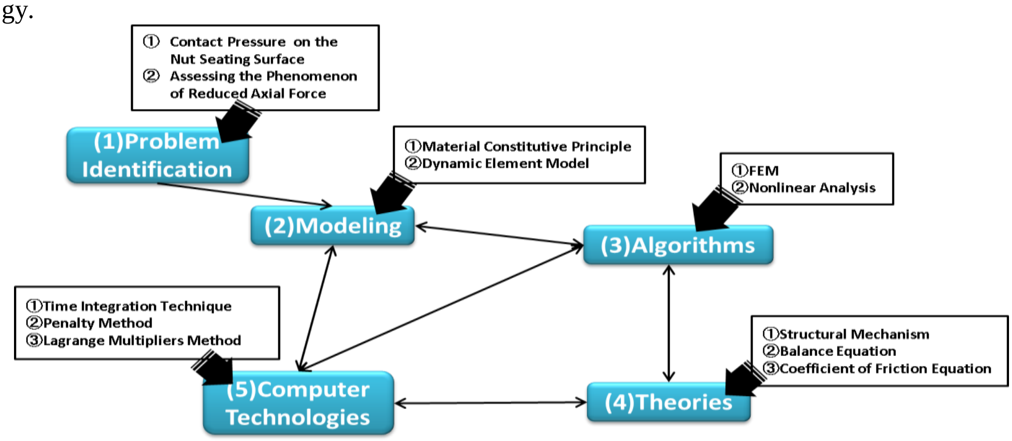

Fig. 15Three-Dimensional Technical Element Model

3.5.1 Problem Identification

We identified the problem as ascertaining the contact pressure on the nut seating surface, as indicated by the example application addressed by this paper, and assessing the phenomenon of reduced axial force.

3.5.2 Modeling

In this section, we model the problem in the form of a mathematical formula. Our dynamic element model used a calculation process that involved applying control to a shape model that reproduced the target objects using CAD [10]. The material constitutive principle is necessary in order to numerically assess the target object's material composition values in order to reproduce the results of actual machine tests.

3.5.3 Algorithms

We used the finite method because it serves as a convenient algorithm. Since it was necessary for us to visualize the contact surface pressure on the nut seating surface in this paper, this approach allowed us to calculate highly accurate results by performing calculations on the level of minute elements. Additionally, we used nonlinear analysis (the Newton-Raphson method) to increase the level of calculation accuracy and set up iterative processing for use when repeatedly calculating, revising, and recalculating solutions [11,12].

3.5.4 Theories

We used the finite element method because it serves as a convenient algorithm. Since it was necessary for us to visualize the contact surface pressure on the nut seating surface in this paper, this approach allowed us to calculate highly accurate results by performing calculations on the level of minute elements. Additionally, we used nonlinear analysis (the Newton-Raphson method) to increase the level of calculation accuracy and set up iterative processing for use when repeatedly calculating, revising, and recalculating solutions.

3.5.5 Computer Technology

Accurate computer technology is the key to a successful CAE analysis. First, we divided the analysis into steps using the time integration method and performed the necessary calculations. Then we used the penalty method to treat the analysis of the contact surface pressure on the nut seating surface of the bolt fasteners, a nonlinear property, as a linear problem. Additionally, we used the Lagrange multiplier method as a substitute for the penalty method at locations at which we wished to perform particularly highly accurate calculations. However, because that approach requires a higher level of calculation speed than the penalty method, it was necessary to consider the give-and-take between quality and delivery timeframe.

3.5.6 Three-Dimensional Analysis Contents

We then performed our analysis using the algorithms of the technical element model for three-dimensional CAE analysis. This process involves choosing various numerical data and analysis methods. For the CAE model, we uniquely determined the material properties in the form of a material constitutive principle model. Additionally, we assigned properties as quantitative values for the constitutive model that defines the material.

In terms of theory, the coefficients of friction serve as important elements. In this case, we assigned the coefficients of friction for the thread and seating surface as quantitative values based on test results. In terms of the calculation technique, we opted to use the penalty method based on consideration of the balance between calculation time and accuracy.

Based on the above considerations, we conducted a finite element analysis using a three-dimensional model taking into account the thread's helical structure and contact.

3.5.7 Result of Three-Dimensional Analysis

Fig.16 and Fig. 17 illustrate the results of an analysis of the contact surface pressure on the nut seating surface immediately after sliding of the seating surface occurred as external force was applied from the bolt part of the bolt fasteners, using the same guidelines as the actual machine test. Both figures show the non-uniformity of stress on the nut seating surface, and it is clear that a high level of stress occurred locally at the beginning of the nut's helical structure. Looking at differences between the two pitches in the area indicated by the red circle, which identifies the beginning of the nut thread's helix, a large amount of stress is distributed across the 0.50 mm pitch nut. In the 1.75 mm pitch nut, the nut has completely loosened and the stress distribution is non-uniform, but there is a high level of stress at the beginning of the thread helix.

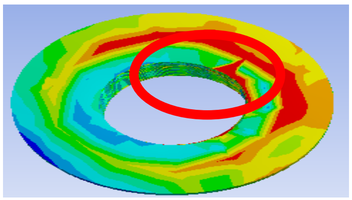

Fig. 16 Result of 0.50mm Pitch

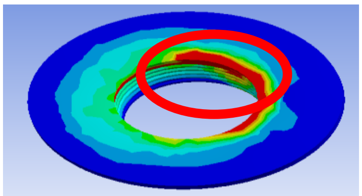

Fig. 17 Result of 1.75mm Pitch

Fig. 18 provides a relationship diagram illustrating the maximum and minimum stress levels observed in the results of the analysis based on the pitch differences (at the nut seating surface). The larger the pitch, the higher the level of stress, and the minimum stress shows a declining trend. Considering the stress amplitude (average of the maximum and minimum stress values), the amplitude increases with the pitch. The results of our analysis showed that the bolt loosens more easily as the stress amplitude increases.

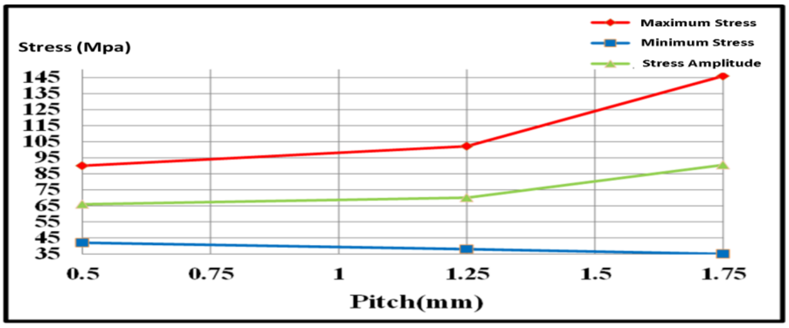

Fig. 18Comparison of Maximum and Minimum Stress on the Nut Seating Surface

3.6 Conclusion of Three-Dimensional Analysis

At this stage, we verified the actual machine tests and CAE analysis results by comparing them from the dual standpoints of time sequence and accuracy. As in the time sequence comparison in Fig. 19 axial force is shown on the vertical axis, and number of vibration cycles on the horizontal axis. Actual machine test results are shown in blue, and CAE values in green. The figure reveals that we achieved an analysis with a good level of accuracy in terms of both the timing at which the bolt loosened and in the extent of the decline in axial force. Furthermore, to verify accuracy, we plotted axial force on the vertical axis versus the start and end points on the horizontal axis in Fig. 20. The broken lines delineate an error of 3% around the test values; since the CAE analysis results fall within those lines, we can conclude that we were able to conduct a highly accurate CAE analysis.

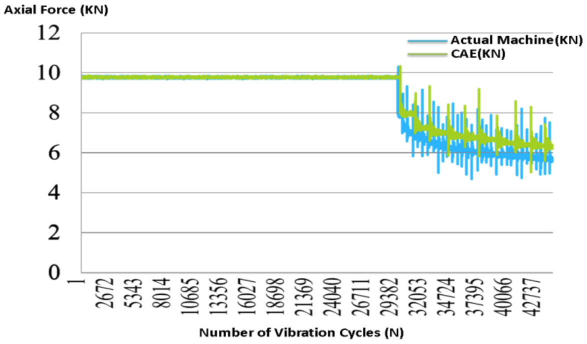

Fig. 19Comparison of Actual Machine and CAE Results (Time Sequence)

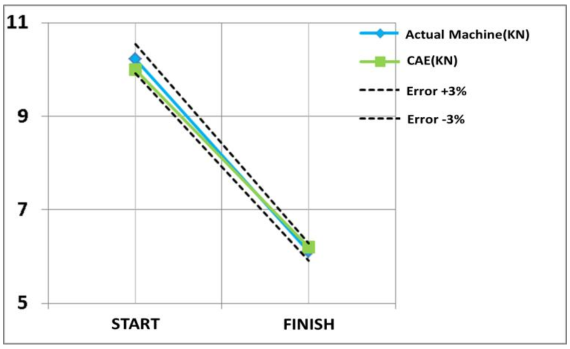

Fig. 20Comparison of Actual Machine and CAE Results (Axial Force)

IV. CONCLUSION

In this paper, we developed a highly reliable CAE analysis approach model to help shorten the development and design stage for various manufactured products. We verified the validity of this model by applying it to an analysis of the nut seating surface in automotive bolts and obtained the expected results by conducting a detailed simulation of stress distribution on the nut seating surface.

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