# Establishment Of Bolt Tightening Simulation System For Automotive Industry Application Of The Highly Reliable CAE Model

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## ABSTRACT

*The automotive industry is engaging in a "global production strategy for simultaneous achievement of QCD (quality, cost and delivery) in an effort to prevail and survive in the "worldwide quality competition". In an effort to realize this, the authors have proposed the high quality assurance system for simultaneous achievement of QCD by a change to super short period development designing, the "Highly Reliable CAE (Computer-Aided Engineering) Model" and demonstrated its effectiveness. To realize this, the rational integration of overall optimality and partial optimality needs to be achieved through the process of "problem – theory – algorithm – modeling – calculator" as a technical requirement to be included in "Bolt Tightening Simulation System".*

**Keywords:** strategic automotive development design, Highly Reliable CAE Model, Bolt Tightening Simulation System

## INTRODUCTION

One of the specific measures taken is an urgent improvement of productivity in the advanced manufacturing processes of planning and development, designing, prototyping evaluation, mass production preparation, and mass production for the purpose of offering highly reliable products to create customer value in a short period of time (Amasaka and Yamaji, 2006). Among other things, a close look at the development designing and production process stage reveals an excessive repetition of "experiment, prototyping, and evaluation" that prevents the "scale-up effect" generated in the bridging stage between prototyping, experiment, evaluation, and mass production. Therefore, innovation of the development and production method, as well as reduction of the development period, is a top priority issue. The automotive industry is engaging in a "global production strategy for simultaneous achievement of QCD (quality, cost and delivery)" aiming to achieve "worldwide uniform quality and production at optimum locations", in an effort to prevail and survive in the "worldwide quality competition" (Amasaka, 2007: 2008).

What is urgently needed is innovation to promote the advance from the conventional evaluation-based development, that uses the prototyping and experiment process (a method based on the confirmation of real goods for improvement) which had long supported the highly reliable designing to CAE (Computer-Aided Engineering) prediction-based designing process for strategic automotive development design. In an effort to realize this, the authors have proposed the high quality assurance system for simultaneous achievement of QCD by a change to super short period development designing, the *"Highly Reliable CAE Model"* and demonstrated its effectiveness.

It solves problems in the calculator that represents modeling in actual matter. When the essence of actual matter is lacking from modeling, the authors can't solve a problem by applying all techniques. A prerequisite for automotive development designing is to derive highly reliable CAE analysis results that show no gap between the actual machine lab tests and the analysis results. To realize this, the rational integration of overall optimality and partial optimality needs to be achieved through the process of "problem – theory – algorithm– modeling – calculator" as a technical requirement to be included in "*Bolt Tightening Simulation System*" (Amasaka, 2007, Yamaji, et al., 2006). It is indispensable in these processes for the CAE engineers to be taken for sophistication of CAE as a problem solving method.

## THE NECESSITY OF CAE IN THE AUTOMOTIVE INDUSTRY

The conventional process of automobile development/production (from planning to mass production) was carried out through the first and the second cycle of "experiment – prototyping – evaluation" (Amasaka and Yamaji, 2006). As a result, it took approximately 40 months from the start of development to the beginning of mass production. Recently however, the development production period of automobile development/production (from planning to mass production) has been further shortened from 2 years to one year, which includes the process of designing – prototyping – experimental evaluation – production preparation – mass production trial. This process is now anticipated by means of (1) SE (Simultaneous Engineering) activities, (2) advancement of CAD/CAM (Computer Aided Design / Manufacturing), IT (Information Technology), (3) introduction of, and a wider range of applications of CAE, and (4) the advancement of knowledge integration, cutting down the number of prototypes and overlapping stages in the "experiment – prototyping – evaluation" cycles required (Amasaka 2007).Against this background of intensifying competition, coupled with the hostage of development and design specialists, has been addressed by increasing CAE investment and bringing in an outsourced workforce.

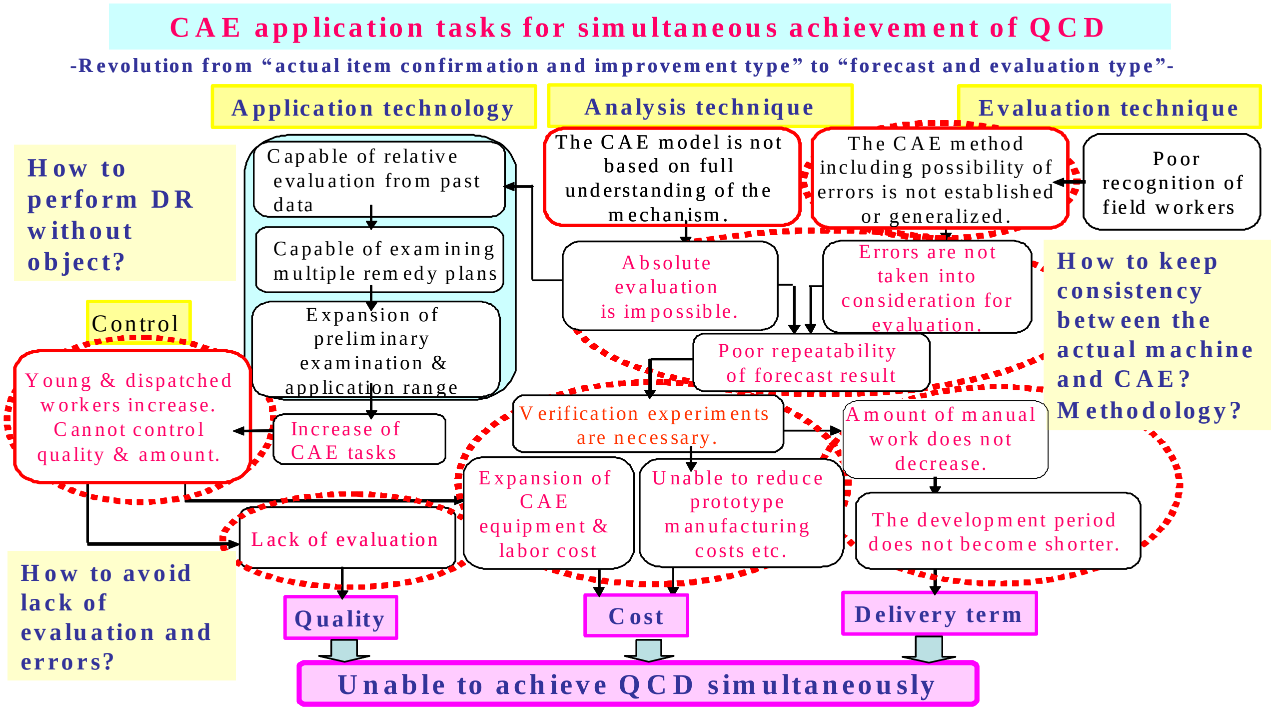


*Figure 1 - Issues When Applying CAE to Development Design Reform*

It has been observed, however, that because of insufficient development of training programs to foster highly skilled CAE engineers, the effectiveness of CAE has been weakened and the authors' development/design process aimed at simultaneous achievement has been hindered (Amasaka, 2007, Amasaka, et al., 2005).

The authors also grasped the effectiveness of as well as problems with CAE utilization and the importance of CAE education and technology succession through a case study of a leading corporation. Also, studies by the authors have demonstrated the effectiveness of incorporating statistical science, which expands the effectiveness of CAE and its range of application. Based on the above knowledge, the "impact of CAE and obstacles to be overcome" are plotted in the relation diagram from the standpoint of "CAE management and simultaneous achievement of QCD" which realizes the high quality assurance of automobiles as shown in Figure 1(Amasaka, et al., 2005).

By summarizing the diagram, it becomes clear that one of the problems in applying CAE for the realization of simultaneous achievement of QCD is the "failure to understand the mechanism of the technical problems encountered and apply it to a CAE" (Amasaka 2007). The second point observed is that, as a substitute for prototypes and experimental evaluation, this CAE analysis proves to be insufficient for reliable prediction and control.

The gap (analysis error) between the analysis and the experimental evaluation data must be as much as a few percent, and at present, the "establishment of CAE software and its usage taking error into account" is not at a satisfactory level. Therefore, despite its expansion, CAE cannot be regarded as making a sufficient contribution to the simultaneous achievement of QCD and reduction in development time (Amasaka, et al., 2005).

## HIGHLY RELIABLE CAE MODEL

For this reason, what is urgently needed, is innovation to promote the advance from the conventional evaluation-based development, that uses the prototyping and experiment process (a method based on the confirmation of real goods for improvement) which had long supported the highly reliable designing to CAE prediction-based designing process, to the establishment of a new development designing technique, the "*Highly Reliable CAE Model*" (Amasaka, 2006: 2007: 2008).

Figure 2 indicates the technical factors involved in highly reliable CAE. This diagram lists the techniques belonging to the domains of (1) problem setting, (2) modeling, (3) algorithm, (4) theory, and (5) calculation technology. These techniques are being used for the purpose of realizing the systemization or formulation of working level problems, development of the kind of algorithms which utilize calculation resources more efficiently, logical analysis of the algorithms, and improvement in hardware and software technology for accelerating the calculation speed. These are the development targets for all kinds of new and old technologies related to computer science which have been actively promoted throughout the world (Yamaji, et al., 2006, Yamaji, et al., 2007).

Far from intending to thoroughly cover the field, this figure simply lists some names of the main techniques in each domain, but it helps us to see the large number of options available for elemental technologies involved in CAE as we try to improve it. However, from the standpoint of implementing CAE as a problem solving method on a working level, the sheer number of, and a wide selection of, these elemental technologies is not sufficient. This is because CAE is thought to be a process consisting of multiple elemental technologies.

Skilled CAE engineers are not experts in all the fields of the elemental technologies, but they understand their characteristics and interactions as "implicit knowledge" and thus conduct selection and combination to obtain favorable interactions and consequently the desired results. The formulation of such "implicit knowledge" confined to the personal know-how of the engineers is an indispensable step to be taken for sophistication of CAE as a problem solving method and therefore it is positioned as a major theme in author's working (Tanabe, et al., 2006).

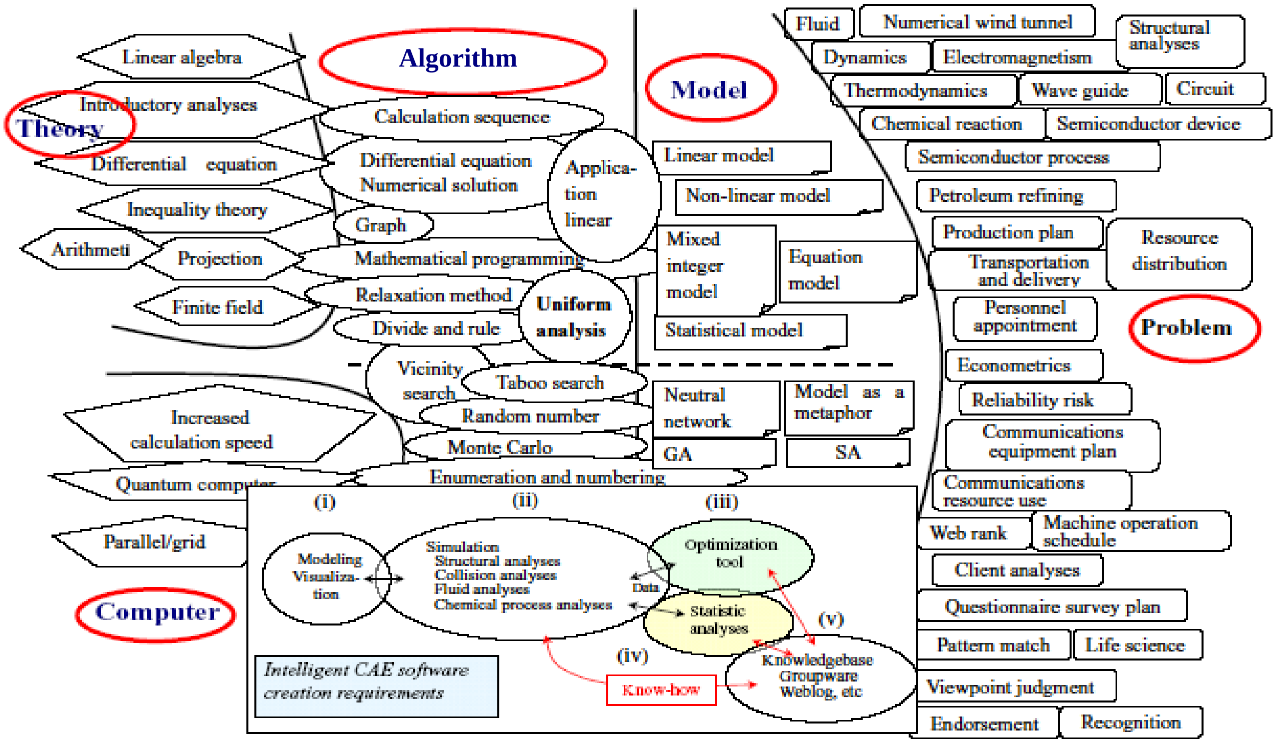


Figure 2 - Highly Reliable CAE Model

## BOLT TIGHTENING SIMULATION SYSTEM

The number of bolts exceeds 3000 in an automobile. The bolts are the mostly used parts in automobile manufacturing and necessary for keeping parts together. For bolts, it is important that axial force and torque are in prescribed sizes for displayed tightening force. If axial force and torque are weak, the looseness occurs by various forces such as inertia force regarding by acceleration, slowdown and vibration force occurs from road surface and engine. Therefore the cracks occur for bolts and substrate by irregular forces. The important quality problems happen if these looseness or crack occurrence during a drive. Therefore, the authors are experimenting and simulating bolt tightening in order to avoid these quality problems (Ueno, et al., 2007a).

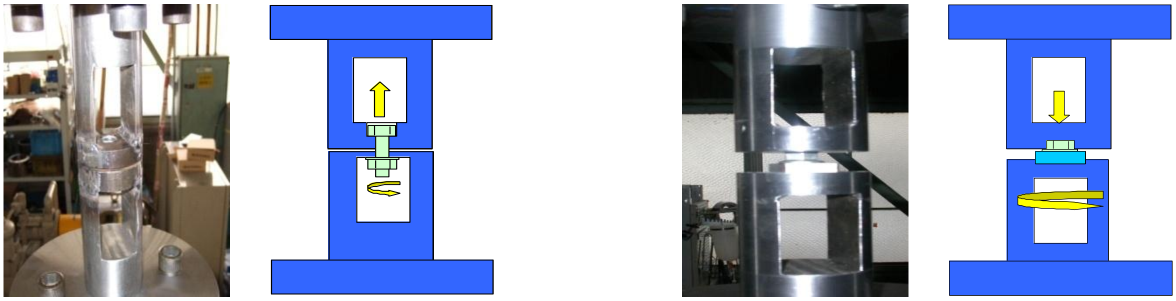
### *Bolt Tightening Experiment*

In this study, the creation of "*Bolt Tightening Simulation System*" one of main elemental technologies for automotive development and design, is featured as part of the in-depth study conducted by utilize *Highly Reliable CAE Model*. This model is expected to realize simultaneous achievement of QCD by means of transformation to a super short-term development and design process for automotive bolt tightening (Mitsuhashi, et al., 2007, Izumi, et al., 2004).

### *Bolt Tightening Experiment Device*

The first, experiment data for bolt tightening is to be collected with a view to reproducing the conditions of bolt tightening by means of CAE. In the case of such defective bolt tightening operations as "looseness" and "cracks" the tightening conditions need to be viewed as initial conditions (Baggerly, 1996, Gamboa and Atrens, 2003, Leea, et al., 2005).

In the above setting, a strain gauge is attached to the material to which hexagon flange bolts are tightened, and an experiment was conducted as shown in Figure 3 in order to confirm an important parameter of the friction coefficient based on the dynamic behavior of "angle * torque * axial force" of (1) the threaded portion and (2) bearing surface (Aragóna, et al., 2005).



*(1) Measuring the friction coefficient of the threaded portion*

*(2) Measuring the friction coefficient of the bearing surface*

*Figure 3 - Measuring the Friction Coefficient to Tighten Bolts*

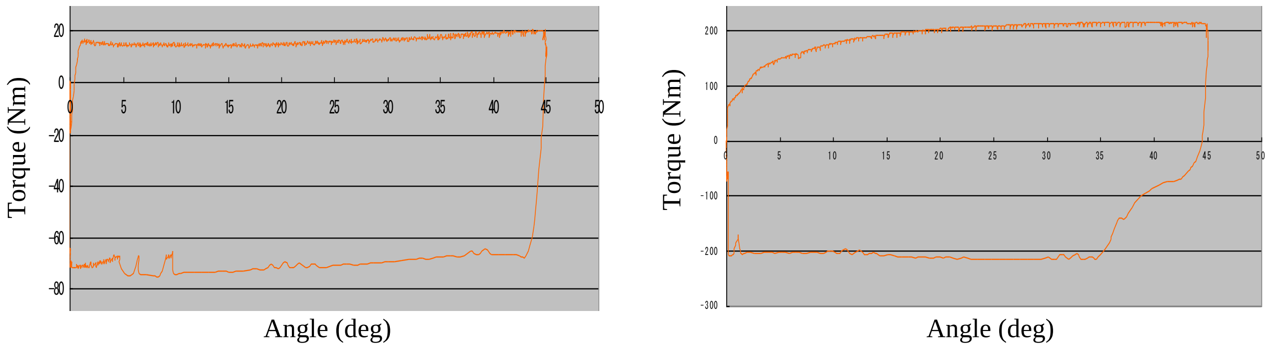
The bolt tightening experiment was conducted using "hexagon flange bolts and hexagon nuts with flange," which are actually used in the automotive industry for commercial use. The friction coefficient of the threaded portion (1) was measured using a 2-axial fatigue testing machine, which is capable of applying axial force and twist force at the same time.

The bolt head was pulled with the force of 20KN, 40KN and 60KN, conducting the experiment for each tensile force five times in total, while torque and axial force were measured. The friction measurement for coefficient of the bearing surface (2) was similarly conducted using the 2-axial fatigue testing machine, applying a compression load of 20KN, 40KN and 60KN onto the substrate while rotating the nut so as to confirm the torque and axial force.

*Results of the Bolt Tightening Experiment*

Based on the results of the friction coefficient measurement of (1) the threaded portion and (2) the bearing surface, torque and axial force were obtained. Applying theoretical equations to these experiment results, the friction coefficients were calculated. Figure 4 below shows the relationship between angle and torque for 60KN of tensile force as well as compression load.

When calculating the friction coefficient of the threaded portion, $\mu_s$ , Equation (1) below was used. Also, the friction coefficient of the bearing surface $\mu_w$ was calculated using Equation (2) (Sakai, 2000, Suzuki, 2005, Tanaka, et al., 1981). Additionally, the bolt and nut dimensions necessary for calculation of these coefficients are given in Table 1.



*(1) Measuring the friction coefficient of the threaded portion*

*(2) Measuring the friction coefficient of the bearing surface*

*Figure 4 - The Relationship between Angle and Torque*

$$\mu_s = \frac{\dfrac{2T_s}{d_2} - F\tan\beta}{\dfrac{2T_s}{d_2}\tan\beta + F}\cos\alpha \tag{1}$$

$$\mu_w = \frac{2T_w}{Fd_w} \tag{2}$$

$\mu_s$ *: The friction coefficient of the threaded portion,* $T_s$ *: The torque of the threaded portion,* $d_2$ *: Pitch diameter,* $F$ *: Axial force,* $\beta$*: Lead angle,* $\alpha$ *: Thread angle,* $\mu_w$ *: Friction coefficient of the bearing surface,* $T_w$*: Torque of the bearing surface,* $d_w$ *: Equivalent diameter of torque on bearing surfaces*

*Table 1 - Bolt and Nut Measurements*

| | Bolt | Nut |
|---|---|---|
| Major diameter of external thread (mm) | 12 | 12 |
| Pitch diameter (mm) | 11.19 | 11.19 |
| Minor diameter of external thread (mm) | 10.65 | 10.65 |
| Pitch of threads (mm) | 1.25 | 1.25 |
| Width across flat (mm) | 16.91 | 16.91 |
| Flange diameter (mm) | 26 | 26 |
| Lead angle (deg) | 2.03 | 2.03 |
| Thread angle (deg) | 30 | 30 |

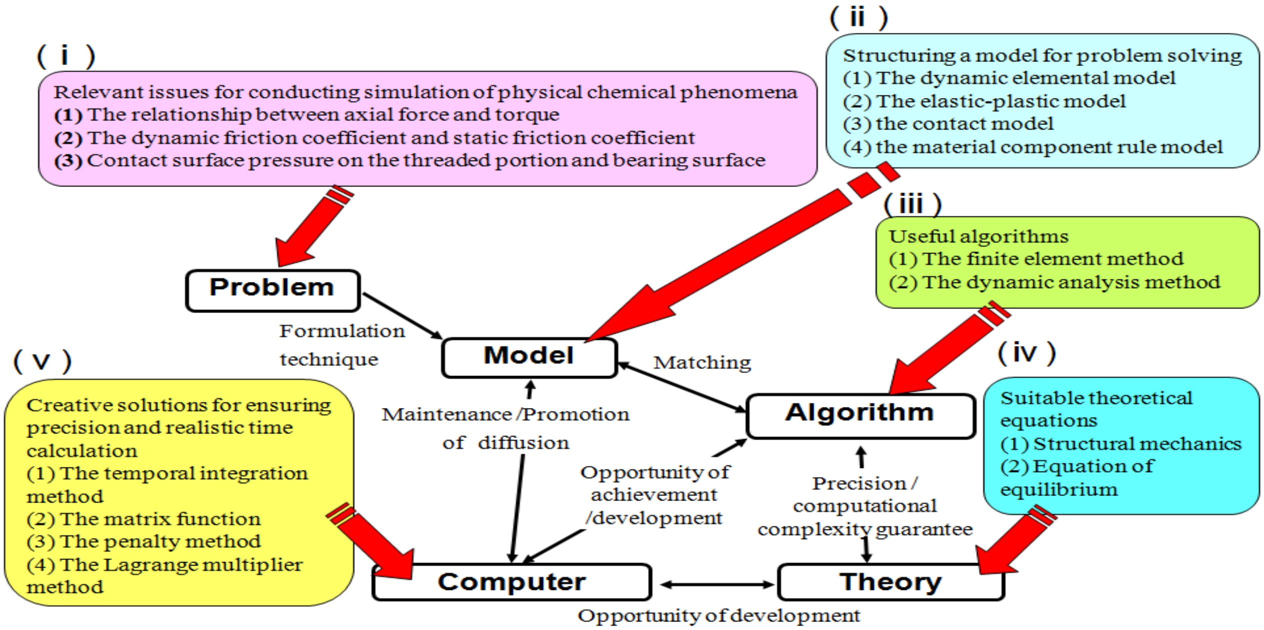


*Figure 5 - The Technological Elemental Analysis of the Bolt Tightening Simulator*

The dimensions of the bolt are actually measured here, and units are in millimeters. However, pitch and other dimensions that are difficult to measure are taken from the ISO standard (ISO15071, ISO15072, ISO4161, ISO10663, 1999). Using equations and dimensions such as those mentioned above, the friction coefficient of the threaded portion and bearing surface was then calculated. As an example, the friction coefficients of the threaded portion and bearing surface when the tensile force and compression load in the axial direction are both 60KN at the angle of 40° are shown in Table 2. Using these calculated friction coefficients, bolt tightening simulation was conducted and the relationship between simulative axial force and torque was confirmed.

*Table 2 - The Friction Coefficients*

| The Friction Coefficient of the Threaded Portion | | | The Friction Coefficient of the Bearing Surface | | |
|---|---|---|---|---|---|
| Angle (deg) | Torque (Nm) | The friction coefficient | Angle (deg) | Torque (Nm) | The friction coefficient |
| 40 | 18.63 | 0.02 | 40 | 215.26 | 0.35 |
| 40 | 23.05 | 0.03 | 40 | 221.63 | 0.37 |
| 40 | 35.30 | 0.06 | 40 | 198.09 | 0.33 |
| 40 | 28.44 | 0.04 | 40 | 208.39 | 0.34 |
| 40 | 32.85 | 0.05 | 40 | 226.53 | 0.37 |

### *Technological Elements of the Bolt Tightening Simulator*

The main issues for creation of CAE software are grasping (1) the actual state of contact between the threaded portion and the grooves, and (2) the friction coefficient of the threaded portion and bearing surface. For structural analysis to function properly, there are two minimum requirements. These are necessary to simulate the dynamic behavior of "angle * torque * axial force" for both the (1) threaded portion and (2) bearing surface during bolt tightening. They requirements are provide contact between the threaded portion and groove, and provide contact between the threaded portion and bearing surface. This should be done on the basis of elastic static analysis and

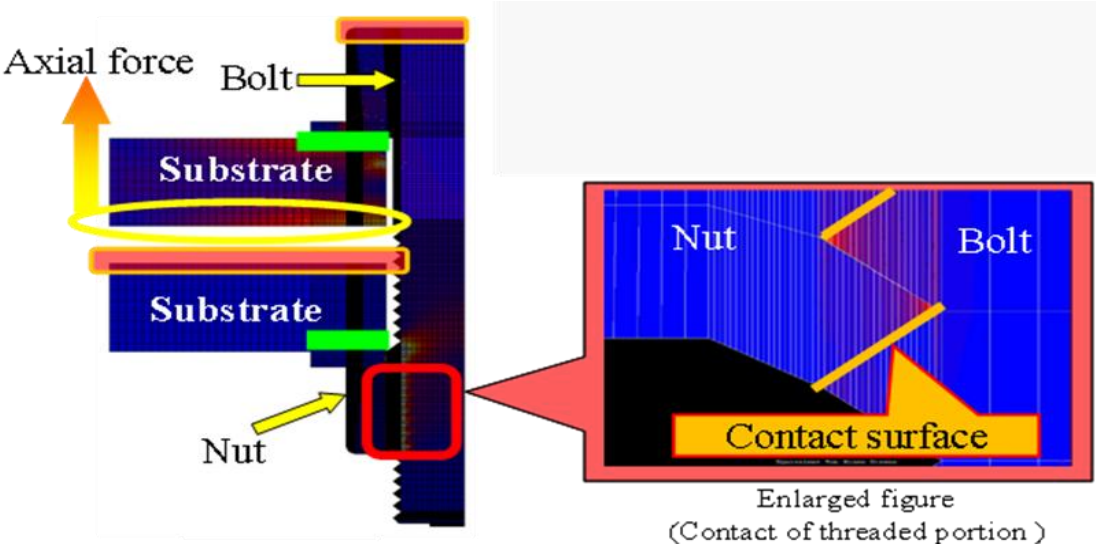


*Figure 6 - The Axis Symmetry Two-Dimensional Model*

elastic dynamic analysis results, calculated using the Finite Element Method (FEM) (Mitsuhashi, et al., 2007). Figure 5 shows the technological elemental analysis of the bolt tightening simulator when the Highly Reliable CAE Model (mentioned Figure 2) is applied.

The figure below shows the following. Relevant issues for conducting simulation of physical chemical phenomena (i) are: (1) the relationship between axial force and torque, (2) the dynamic friction coefficient and static friction coefficient, and (3) contact surface pressure on the threaded portion and bearing surface. Models for solving these issues (ii) are: (1) the dynamic elemental model, (2) the elastic-plastic model, (3) the contact model, and (4) the material component rule model, Useful algorithms (iii) are: (1) the finite element method and (2) the dynamic analysis method. (iv) Suitable theoretical equations are: (1) structural mechanics, and (2) equation of equilibrium. Finally (V) examples of creative solutions for ensuring precision and realistic time calculation are: (1) the temporal integration method, (2) the matrix function, (3) the penalty method, and (4) the Lagrange multiplier method. These are to be utilized to compose a bolt tightening simulation system.

### *Development of the Bolt Tightening Simulation System*

Many bolts are used in the assembly of automobiles, and they must be tightened in such a way as to ensure the strength (safety) of the areas in which they are used. With this in mind, the authors developed the *Bolt Tightening Simulation System (BTSS)*, applying the aforementioned bolt tightening simulator (Ueno, et al., 2007b).

This analysis utilizes the axis symmetry two-dimensional model as shown in Figure 6. The analysis parameters are the same as the experiment parameters. Regarding the analysis parameters, axial force is applied to part of the upper substrate and the bolt bounded from all directions in the same way as it is applied to part of the bolt head and lower substrate. The friction coefficient was calculated by conducting experiments on parts of the contact bearing surfaces and the contact surface of the threaded portions, and then inputted into CAE simulation software. In addition, the authors compared the relationship between torque and axial force using the results from the experiment and simulation analysis.

The results of this comparison are shown in Figure 7. The results of the experiment are represented by the blue line and the results of the simulation analysis are represented by the red line. This chart shows that the results of the simulation analysis closely match the results of the experiment. Therefore, the authors are immediately applying the knowledge gained from conducting analysis such as this, and conducting bolt tightening simulation analysis on three-dimensional models to enable analysis of looseness and cracks.

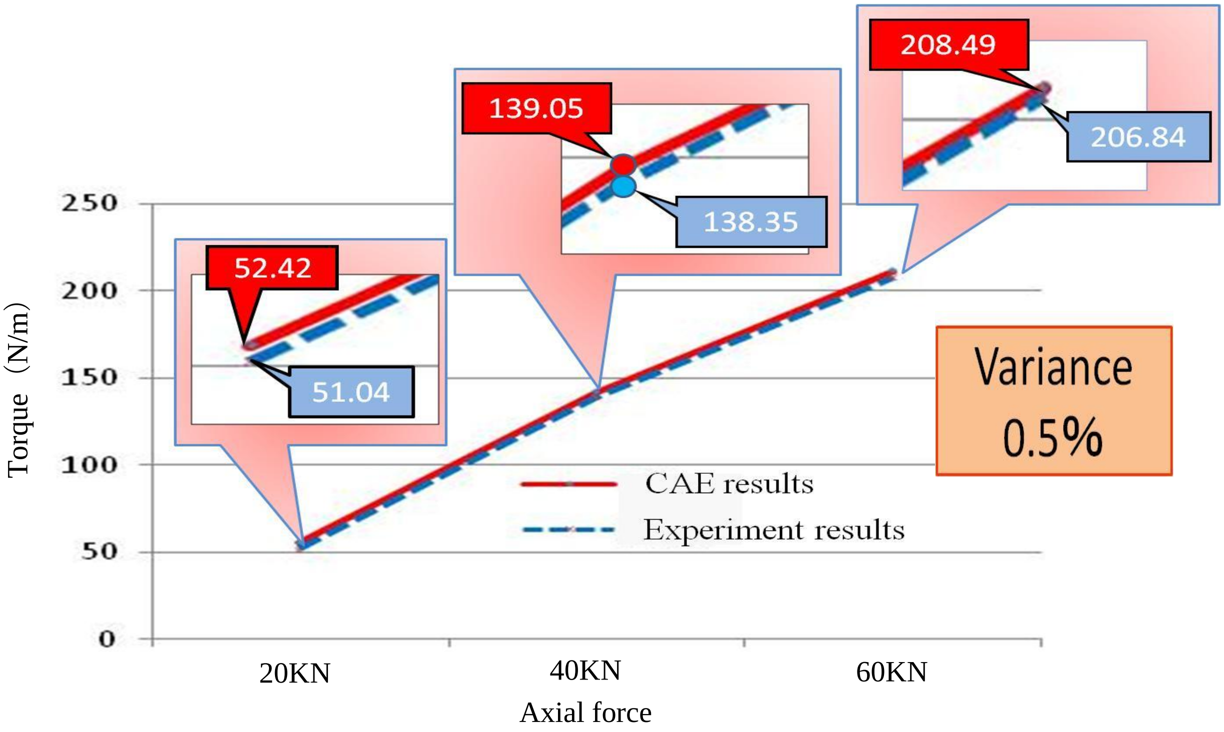


*Figure 7 - Comparison Result*

## CONCLUSION

The automotive industry is engaged in a “global production strategy for simultaneous achievement of QCD” in an effort to survive and prevail in the “worldwide quality competition”. Therefore the authors have established the *Bolt Tightening Simulation System (BTSS)*, for the application of the *“Highly Reliable CAE Model”*. The purposes of this system are (i) to determine the factors necessary to understand the behavior of bolts during tightening, (ii) to measure the angle, torque and axial force during bolt tightening. This has enabled the authors to calculate relational errors in axial force and torque compared with measurements and simulation results to within a range of less than ±0.5%. In their efforts to achieve this, the authors proposed the application of the *“Highly Reliable CAE Model”* and have demonstrated its effectiveness.

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## NOTES