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Division V

APPLICATION OF ANALYSIS FOR ASSEMBLY OF INTEGRATED COMPONENTS TO STEEL MEMBER CONNECTIONS TOWARDS SEISMIC SAFETY ASSESSMENT OF PLANT STRUCTURES

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ABSTRACT

In this research, we aim to develop a connection modeling method that reproduces more realistic behavior by utilizing a three-dimensional well described model of the connection. As the first step of the targeted assessment procedure utilizing the developed three-dimensional model, we modeled a connection of the steel structure with advanced finite element analysis (FEA) and confirmed the validity of the analytical method by comparison with experimental results. Using the validated analytical method, numerical experiments are conducted on the structural strength and stiffness.

The result of this advanced FEA of the connections is transformed into a macroscopic parameter of a rotational spring element in the frame analysis model which has been widely utilized in the conventional design method. The rotational spring constant of the advanced FE models is calculated to be reasonably close to that of the referenced experiment. In addition this study reveals that the advanced FEA can become proper technique to investigate on microscopic features such as the gap between the contact surfaces, which is highly necessitated for studying impacts on the structure by initial conditions caused at the construction site, or durability factor such as corrosion effects.

By applying the obtained results to the modeling of the connections of a steel structure, such as the roof truss of the nuclear reactor building and the exhaust tower, etc., it is expected that the proposed method / model can be developed for grasping the vibration properties and identifying the strength and stiffness, etc., for seismic safety assessment of a nuclear plant structure.

INTRODUCTION

Exhaustive studies on external events that may pose a threat to the structures of nuclear facilities and evaluations of the structural integrities are critical to safety. Especially in Japan, where earthquakes occur frequently, it is a crucial task to identify the behavior of the nuclear plant structure during an earthquake and to ensure that the seismic response evaluations are as realistic as possible. One of the components that greatly influence the behavior of the plant structure during an earthquake is the connection of steel structural members. In particular, the modeling of the connections has relied on empirical methods, and been conservatively designed and evaluated by considering them as pinned connections or fixed connections.

Federal Emergency Management Agency (FEMA) said, “A beam-column connection assembly was routinely specified by designers in the period 1970-1994 and was prescribed by the Uniform Building Code for seismic applications during the period 1985-1994. It is no longer considered to be an acceptable design for seismic applications. Following the Northridge earthquake, it was discovered that many of these beam-column connections had experienced brittle fractures at the joints between the beam flanges and column flanges.” FEMA had published FEMA-355D, "State of the Art Report on Connection Performance" as a part of Program to Reduce the Earthquake Hazards of Steel Moment-Frame Structure in September, 2000. FEMA-355D describes understanding the behaviour of steel moment-frame buildings in earthquakes. The report spends the cyclic inelastic behaviour of beam column connections. It has remarked that bolted connections offer substantial advantages for seismic design, though the failure modes and yield mechanisms of bolted connections are more complex than welded one. It has stated unresolved issues such as the models for predicting connection performance and balancing connection behaviour to be revealed. See SAC Joint Venture. (2000). Extended researches are published, such as See Mays (2000), Sumner (2000), though they are giving understanding for phenomena and influence in seismic design to develop guidelines for the seismic evaluation, inspection and so on.

Japan Atomic Energy Agency (JAEA) had strong interests on these issues, and developed FIESTA (Finite Element Analysis for Structure of Assembly) to discipline the connection assembly analysis. The authors had reported a steel structure of a petrochemical plant built into a finite element model as an assembly of integrated components. Time-history response analysis was conducted with high-performance computer technology to show the feasibility of this analysis method (Nakajima et al., (2015)). The essence of this highly-sophisticated finite element analysis (FEA) was adopted for the steel member connections of a structure. Also, See Nishida (2006). This paper also discussed a matter of fundamental function of FIESTA.

In this research, we aim to develop a connection modeling method that reproduces more realistic behavior by utilizing the advanced three-dimensional modeling method we developed. As the first step of the targeted assessment procedure, we planned to model the connections of steel structural members in a plant structure, and perform elastic and non-linear analyses to reveal the mechanism of bolted connection assembly. The connections are sufficiently detailed to reveal the mechanism and the validity of the analytical method by comparison with experimental results. Using the validated analytical method, numerical experiments are conducted on the structural stiffness. To discuss an ability of finite element analysis, ABAQUS was selected to perform the calculation (Fish (2008)). And the results of this advanced FEA of the connections is transformed into a macroscopic parameter of a rotational spring element in the frame analysis model which is widely utilized in the conventional design method.

This research aims to clarify the stress conditions and deformation in the connection utilizing the highly advanced calculation with the advanced FE model, and also to discuss the necessity of applying the advanced FEA to the conventional design method. Although the paper discusses within the elastic range, this research will extend to the study of structural behaviors in the plastic range considering the seismic design in relation with the relevant codes and standards such as AISC 341.

MODELS FOR NUMERICAL EXPERIMENT

At first, we compare the experimental results with the analysis results and verify the validity of the analysis method. Sumner (2000) conducted the cyclic test of bolted moment endplate connections as SAC steel project. Since Sumner (2000) gave experimental results, a fundamental model is drafted in Figure 1 to compare with. The model consists from a column and a beam connected with an endplate by some bolts. A finite element model is shown in Figure 2. In the finite element analysis model, material is assumed as steel and Young’s modulus is set to 210,000 MPa, Poisson’s ratio is to 0.3, and density is to 7.8×10^{-9} t/mm^3. The top and bottom of the column is completely restrained, and a forced displacement

(300 mm) is applied to the end of the beam. For analyses' cases, a continuous model was implemented that every connection of components' finite element node is merged to a node. Otherwise, the nodes on the attached surface are shared with each component.

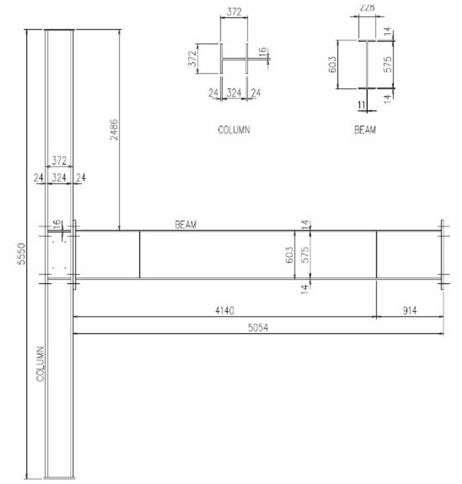
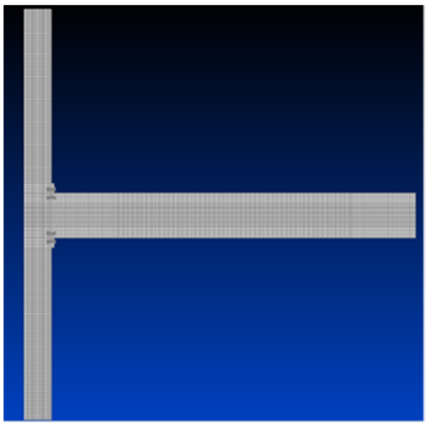
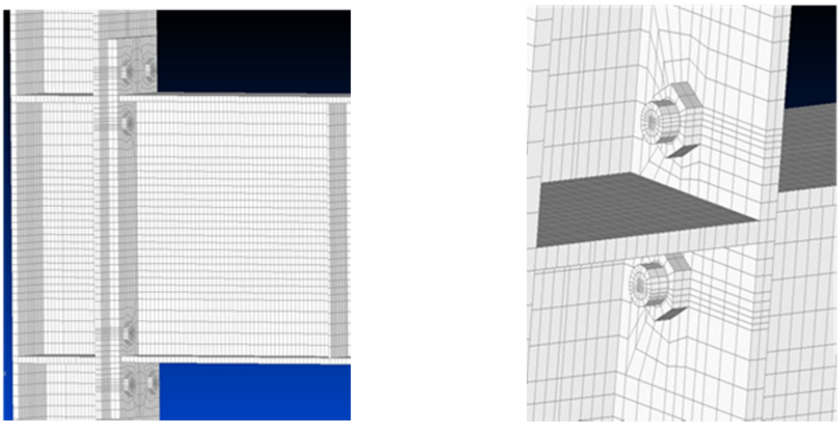


Figure 1. A draft of a fundamental model for numerical experiment



(a) Overview of a model



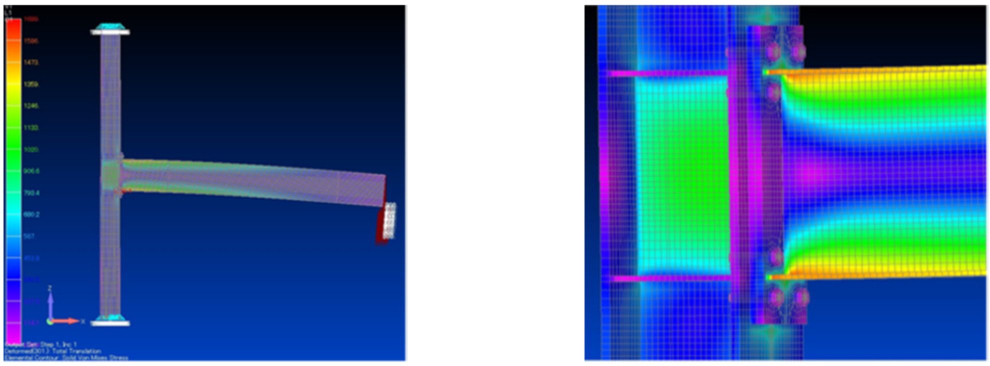
(b) Connection parts of a model
(c) Bolts tied parts of a model

Figure 2. A finite element meshed model for numerical experiment

NUMERICAL EXPERIMENTS

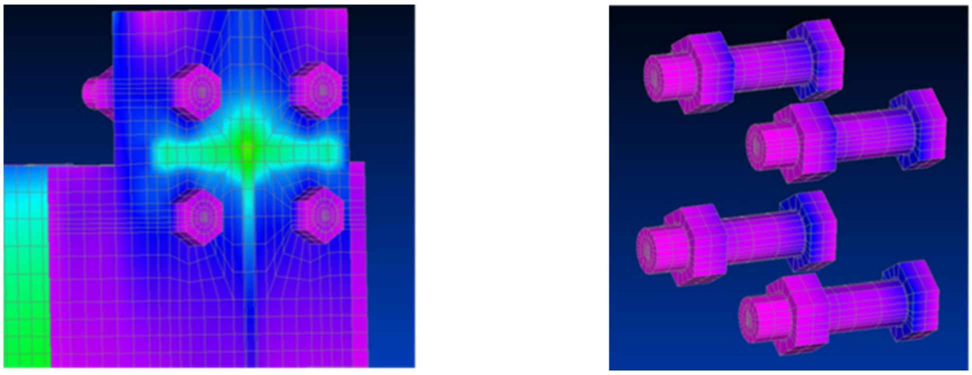
Welded model

The continuous model introduced in the former clause is defined as welded model and it is calculated by ABAQUS to be a reference to the bolted connection model to be introduced in the next clause. The analytical results are shown in Figure 3. The endplate and the column are completely fixed so that no slip displacement occurs and the von Mises stress is symmetrical with respect to the center of the joint. It is found that the von Mises stress of the beam is much larger than that of the endplate, especially in the flange part of the beam. The bolts bear almost no axial force, and no stress concentration occurs.



(a) Overview of a result with von Mises stress distribution

(b) A result with von Mises stress distribution for connection parts



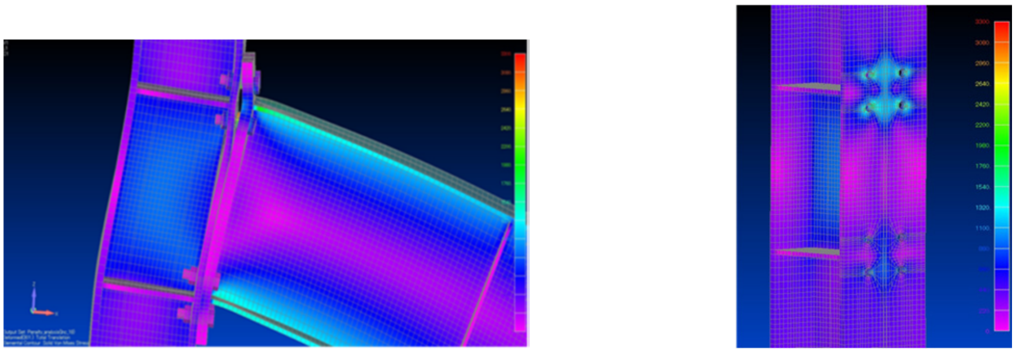
(c) A result with von Mises stress distribution for bolts tied parts

(d) A result with von Mises stress distribution for bolts

Figure 3. Numerical experiment results for a welded model

Bolted connection model

In the bolted connection model, all surfaces in contact between the nut and the column, the column and the endplate, and the endplate and the bolt are defined as contact surfaces. Due to the discontinuity at the joints, the endplates and the columns are fixed by tightening the bolts. To confirm the effect of the pre-tension of the bolt, two types of connection are considered, without and with pre-tension of the bolt. Figure 4 show the analytical results of the bolted connection model without pre-tension. In this case, unlike the welded model, the stress distribution is asymmetrical. It is found that the local deformation of the endplate reduced the stress of the beam. Large stress concentration occurs in the four bolts at the top of the endplate to be pulled.



(a) Overview of a result with von Mises stress distribution on a deformation

(b) A result with von Mises stress distribution for connection parts

(c) A result with von Mises stress distribution for Bolts tied parts

(d) A result with von Mises stress distribution for Bolts

Figure 4. Numerical experiment results for a bolted model without pre-tension

Next, the bolted connection model with pre-tension is considered. The bolt pre-tension is assumed about 55 kips = 244,640 N (Mays (2000)). The analytical results for the bolted connection model without versus with pre-tension are shown in Figures 5 and 6. As the results, bolt pre-tension does not significantly affect the behavior of the entire structure in its deformation, although its stress distribution is totally different.

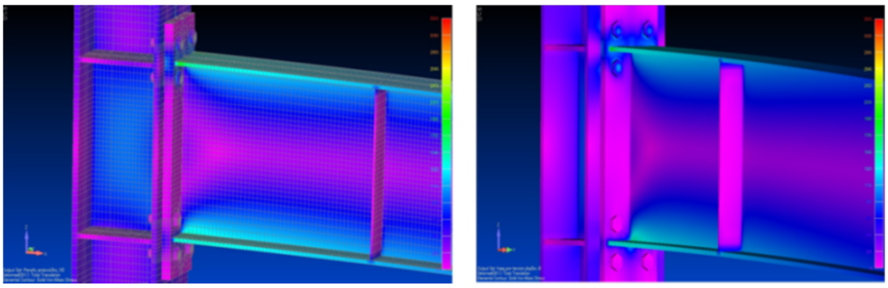
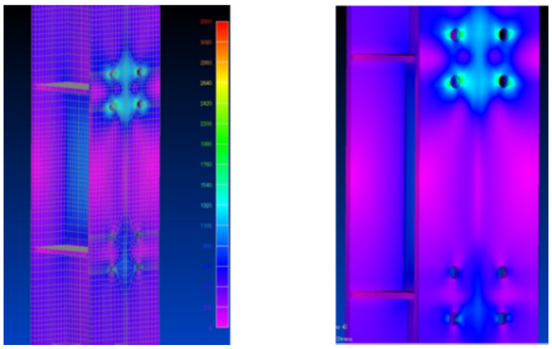
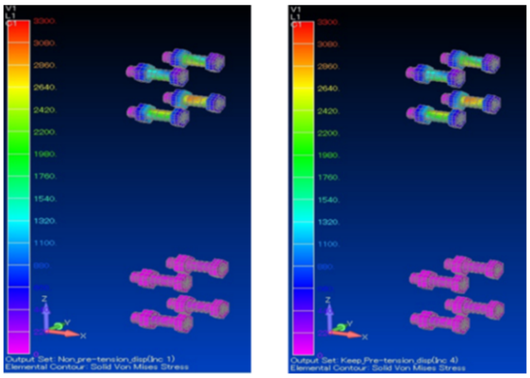


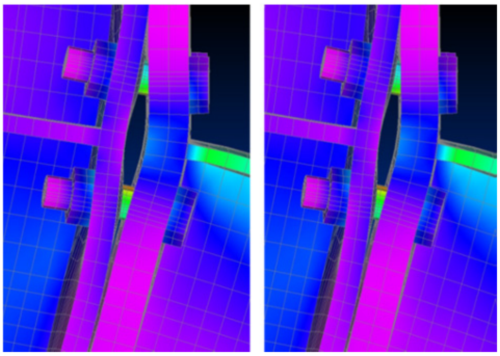
Figure 5. Numerical experiment results and comparisons for bolt connection models without (left) versus with (right) pre-tension (1/2)
- Overview of a result with von Mises stress distribution -



(a) A result with von Mises stress distribution for connection parts



(b) A result with von Mises stress distribution for bolts



(c) A result with von Mises stress distribution for endplate and attached column

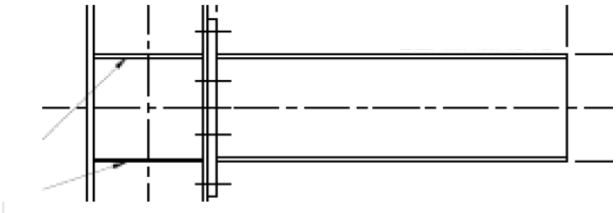
Figure 6. Numerical experiment results and comparisons for bolt connection models without (left) versus with (right) pre-tension (2/2)

RESULT DISCUSSION

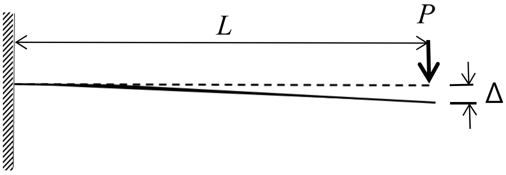
The results of the numerical analysis for the advanced FE model of the connection are compared with the rotational stiffness which is a macro-parameter of the connection in the frame model for analysing whole structure. As illustrated in Figure 7, a beam-column connection (of which actual configuration shown in (a)) is modelled into either (b) a fixed boundary condition, or (c) a rotational spring element at the node connecting beam elements in a conventional frame analysis model. As shown in (d), the vertical displacement of the advanced FEA becomes larger than the theoretical solution of the beam with fixed end (i.e. idealistic assumption of no rotation at node), and in order to align to the realistic displacement, a rotational spring element (having local rotational stiffness, K', which is smaller (more flexible) than global rotational stiffness, K, defined later) is generally provided in the conventional frame model.

Although the connection in the advanced FE model does not actually behave as simple linear rotational spring due to variations in stress generation in parts assembled such as bolts, endplates, it would cause negligible difference in the connection as a whole especially in the elastic region.

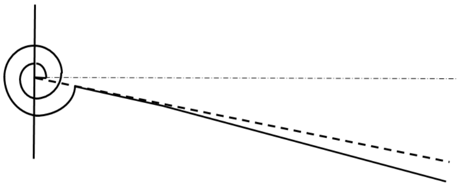
In the advanced FEA, a forced displacement, Δ, is given at the loading point of distance L from the center line of the column, and the equivalent load, P, is back-calculated from the internal stress generated in the FE model. In Figure 8, the results of the advanced FE models and the frame models with various boundary conditions are expressed in terms of bending moment, $M = PL$, as function of global rotational angle, $\alpha = \Delta/L$. The slope of each line, which is the global rotational spring constant, $K = M/\alpha$, and its ratio to the theoretical answer of the cantilever beam are summarized in the Table 1.



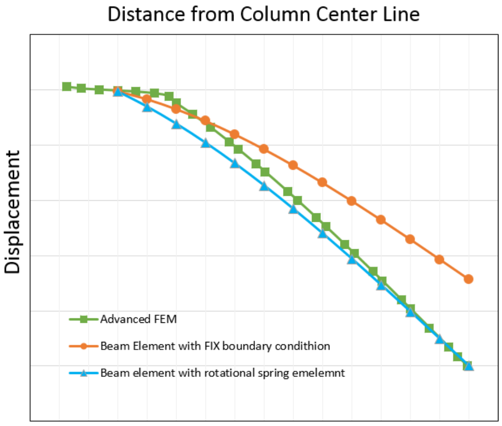
(a) Actual configuration



(b) Beam element with fixed boundary



(c) Beam element with rotational spring element



(d) Beam displacement curve for each condition

Figure 7. Frame modelling of beam and comparison of analysis results with FE Model

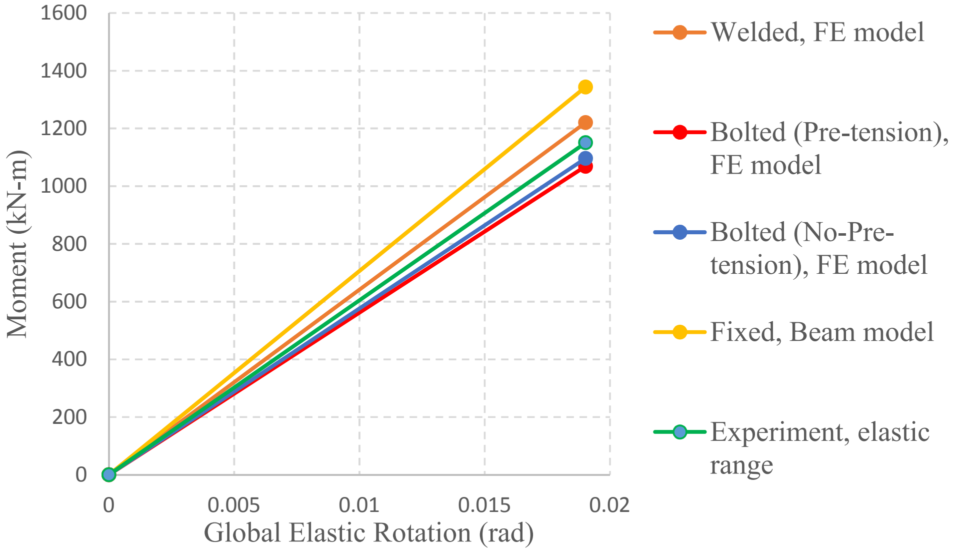


Figure 8. Relation between bending moment and global rotation (comparison with experiment)

Table 1: Global rotational spring constants and comparison with experiment

	Global spring constant (kNm/rad)	ratio
Fixed, beam model	70,604	100.0%
Welded FE model	64,140	90.8%
Bolted FE model without pre-tension	57,616	81.6%
Bolted FE model with pre-tension	56,172	79.6%
Experiment	60,474	85.7%

The global spring constant, *K*, becomes the largest in the beam model with fixed end, and then that in welded FE model, bolted without pre-tension FE model, and bolted with pre-tension FE model, follows in decreasing order. It is reasonable that the global spring constant of the welded FE model becomes larger than those of the bolted FE models because there exist a gap between the endplate and the column in the bolted models. The gap between the contact surfaces in the bolted models at the elastic limit of the connection, $\alpha = 0.019$ rad. is 0.64 mm without pre-tension, and 0.53 mm with pre-tension, and this difference among models without and with pre-tension is considered negligible in terms of the structural behavior of the global spring constant in the elastic region. However in the reality, the gap will increase abruptly after the yield point and so is the global spring constant, thus it is necessary to analyze the connection with the advanced FE model with elastoplastic parameter assumptions.

The global spring constant in the reference experiment falls 4 -6% larger than that of the bolted FE model, 5% smaller than the welded FE model, and 14% smaller than the beam model with fixed end. The rotational spring constant calculated with the advanced FE models of the connection (regardless of welded or bolted) is closer to the experimental value than that calculated with the frame model with fixed boundary condition. It is thus confirmed that modelling procedures and assumptions adopted in the advanced FEA are reasonable. In other words, instead of the discrete boundary conditions of fixed-pinned adopted in the conventional design method, the frame model analysis using the rotational spring constant calculated with the advanced FE model gives more reasonable and accurate results. In addition, the conventional method adopting the fixed-pinned assumptions is confirmed effective in order for the design calculation in the safe side.

As this study in the first stage reveals that the advanced FE model can provide a macroscopic parameter of the rotational spring constant reasonably close to the real conditions, the next step will be to investigate on microscopic features such as the gap between the contact surfaces relating to initial conditions caused at the construction site, or durability factor such as corrosion effects, in which the advanced FEA is expected to work powerfully.

CONCLUSION

Towards more accurate analyses including those for seismic events of the steel structures in the industrial facilities such as nuclear plants, a study to elaborate the frame analysis utilized in the conventional design by conducting the advanced FEA targeting the column-beam connection, is carried out. As the first step, elastic analysis with non-linear effects of continuous and contact models simulating the welded and bolted connections without and with bolt pre-tension, were conducted. This analysis in the elastic region tried to trace the bending test of the steel column-beam connection of actual scale presented in reference.

Taking the rotational spring constant as the macroscopic parameter at the node of the frame model to be evaluated, the rotational stiffness of the contact FE model (called as bolted connection model) became about 5% smaller than that of the continuous FE model (called as welded model). This is caused by the difference in configuration of two connection models, specifically by the gap between the column and endplate in the bolted FE models, which is clearly observed even with the elastic analysis model. It was also confirmed that the difference in the rotational spring constant between bolted models without and with pre-tension is negligibly small as about 2 %.

The deviation in the rotational spring constant of the advanced FE models (regardless of bolted or welded) from the actual test, was calculated to be in an order of ±5%, whereas the deviation of the beam model with fixed end that routinely used in the conventional design method from the experimental result was in an order of +10%. It is obvious that the method utilizing advanced FE models proposed in the paper is considered reasonable. For the next step, the advanced FE models will be analyzed with elastoplastic material properties to grasp the behaviors of the connections in the plastic region, and by clarifying the mechanism of force transition in the connection, how its configuration (dimensions, shape, parts assembly) relates to the stiffness and the deformation capacity as a whole will be studied in detail.

In order to establish reasonable means in the design process, the detailed analytical study as performed in the paper is confirmed effective. The authors would like to promote studies and applications of advanced analytical technique to the practical engineering with continuous cares taken for safety and security of the society, e.g. elaboration of damage evaluation or analysis process, realization of manufacturing and construction process of sounder structures.

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