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# HYBRID AND PARALLEL STATIC ELASTIC-PLASTIC STRESS ANALYSIS COMBINED WITH PARTIAL ACTUAL EXPERIMENT

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## ABSTRACT

The structural design is the decision for the members in the structures not to be destroyed and to be maintained safely, when external disturbance occurs such as earthquakes and strong winds. It is necessary to confirm the safety for buildings by making the actual scale building and checking the behaviors in the structure with experiments. However, it costs very high. It is that behaviors and safety of structures are evaluated with the numerical models and the numerical stress analysis by the computers. We need to evaluate the numerical the numerical models for the material characteristics with acting forces for each member exactly in the case of the numerical stress analysis. However, it is quite difficult for the engineers to evaluate the complicated models for members. We developed a hybrid and parallel stress analysis system. All the behavior in the structures is acquired by this system with combination the actual experiment for complicated material members and the numerical stress analysis for other parts with a sub-structuring method. We can study behaviors in the members as the part of all structures under real circumstances not as isolated specimen. In this paper, the method is described and an actual example of the plane steel frame as the verification for this system is showed. It is proven that the good results would be acquired by using this system.

## KEYWORDS

Non-linear numerical stress analysis, Hybrid and parallel stress analysis, On-line sterss analysis, Electric actuator, Stepping motor

## PREFACE

It is necessary to evaluate the numerical models against complicated material characteristics for each member in the numerical stress analysis. However, it is quite difficult to evaluate such numerical models for all member in the structure with considering behaviors of columns in that there are many changes for axial forces or of complicated panel zones. The quite complicated numerical models would be applied, even if they could be evaluated. It has been hard to connect loading conditions such as sizes, distribution and loading time history to all behaviors in the structure as a whole at each test in the case of using test pieces as one beam or one column. It was impossible to reproduce a complicated behavior of a member with considering influences such as flows of forces from members around it. We developed a new hybrid and parallel static elastic-plastic stress analysis system combined with partially actual experiment called experimental analytical system in this paper. In this system, complicated material characteristics, that are quite difficult to evaluate the numerical models for structural members, are acquired with performing the actual experiment and the they are transferred to a personal computer system that performs the elastic-plastic numerical stress analysis for the frame structure. This system performs both a stress analysis and an experiment for the structure simultaneously by controlling the actuators with adapting the compatibility for forces and displacement on the boundaries both for analytical parts and experimental parts of the structure. concept of this system is shown in Fig. 1. As many on-line experiments combined with both an experiment and a stress analysis have been performed, there have been almost cases that are adapted for simple structures. In this paper, we show the summary, the method and the result of the verification test with the steel frame structure with three floors and two spans. The used numerical stress analysis was composed of non-linear static sub-structure method and the left side column, in that the changes of an axial force are large, was used as the actual experimental member. Three electric actuators were used as the controller.

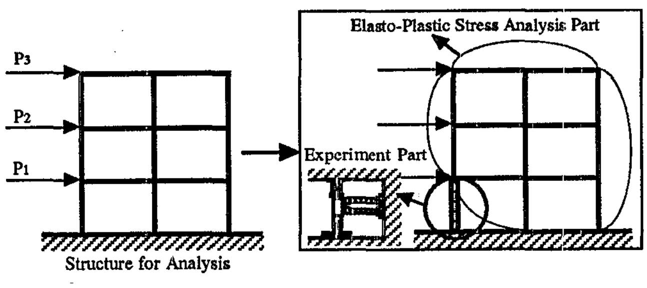



Fig. 1 Concept of this system

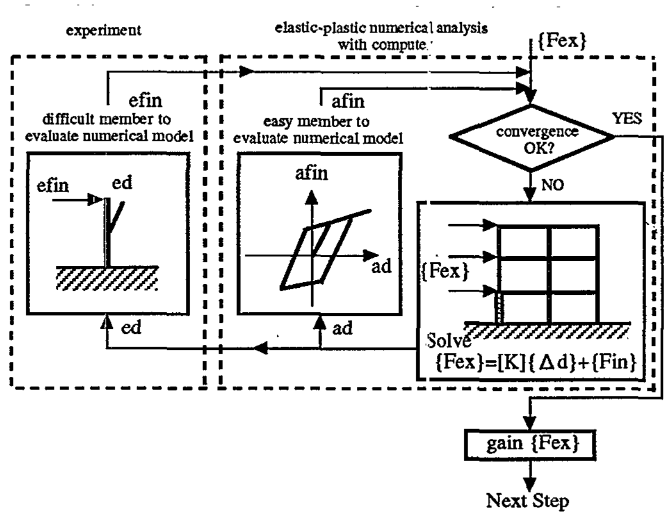



Fig. 2 Flow chart of this system

## SUMMARY OF EXPERIMENTAL AND ANALYTICAL SYSTEM

The flow diagram of this system is shown in Fig. 2. As it is not possible to evaluate the element stiffness sized 3 by 3 for an experimental member at each loading step, the numerical stress analysis with one personal computer for all the structure was performed to evaluate the displacements and nodal forces by using the elastic element stiffness for the experimental member at each step. Then a horizontal displacement, a rotational angle and a vertical nodal force acquired from the numerical stress analysis were adapted to the top of actual column called an experimental member by using three electric actuators controlled with other personal computer. At this situation, another horizontal force and bending moment was evaluated by combining data measured from equipment such as load-cells and displacement meters by using other personal computer and numerical stress re-analysis was again performed by using difference between nodal forces acquired from analysis and ones from experiment as revised loads to re-evaluate displacements with them until re-evaluated displacements were almost zero. This experimental and analytical system was progressed to the next loading step, after the convergence was reached. It is necessary to adapt the vertical displacement calculated from numerical stress analysis and reflect vertical force, that was evaluated from measurements to the re-analysis. However, a vertical force acquired from numerical stress analysis was adapted on the top of column directly, because it was difficult to control the vertical displacement with the electric actuator, as it was quite small.

## COMPONENTS OF THIS SYSTEM

The components of the system were shown in Fig. 3. The systems were composed of two personal computers and loading equipment such as test frame. One personal computer was used for numerical stress analysis and another was used for the control of actuators and measurement from equipment such as load-cell, strain gages and displacement meters. Loading equipment must be accurate to apply exactly nodal displacements acquired from numerical stress analysis on the specimen. It is difficult to control displacements with high accuracy by using the oil jack that has been using until now. We made three electric actuators, that can rotate for a constant angle exactly with every pulse signal and bear little accumulation for angle errors, as a source of power, and used them in this system.

## SOFTWARE FOR THIS SYSTEM

The flow chart of software for this system and numerical stress analysis is shown in Fig. 4. The right part in the flow chart is the flow of a program for the numerical stress analysis and the left part is the flow of a program for the controlling actuators and for measurements. The thick line shows a communication of data with RS232C. Commands for controlling actuators, data for nodal displacements and a nodal force at the top of column were sent from the personal computer for numerical stress analysis. It was possible to perform measurements by using equipment and communication for all data to send and to accept automatically. Data sent from the personal computer for controlling actuators and measurements were reaction forces at the top of a column that was used as experimental specimen.

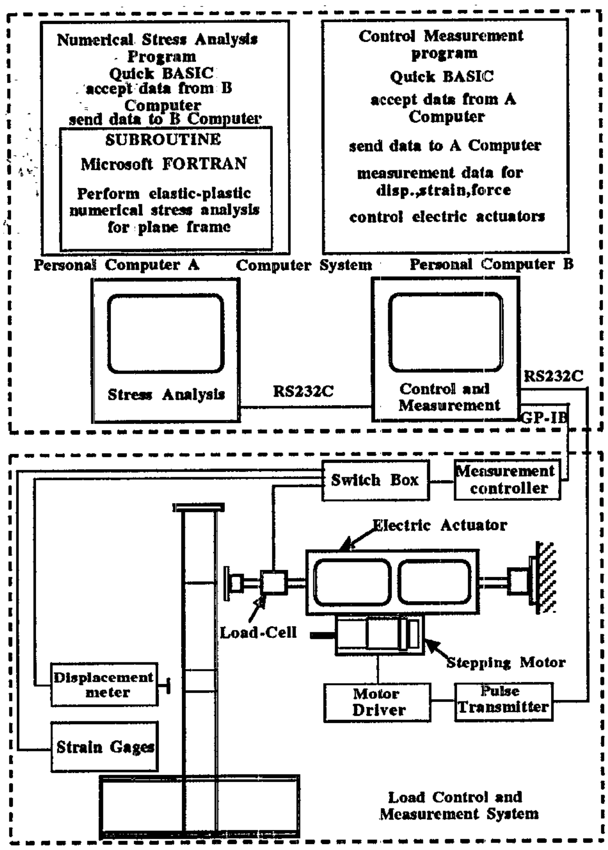



Fig. 3 Conponents of this system

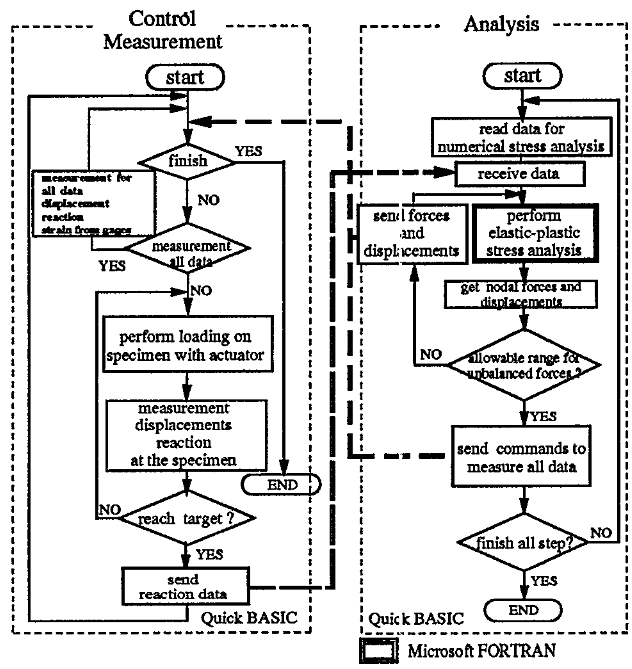


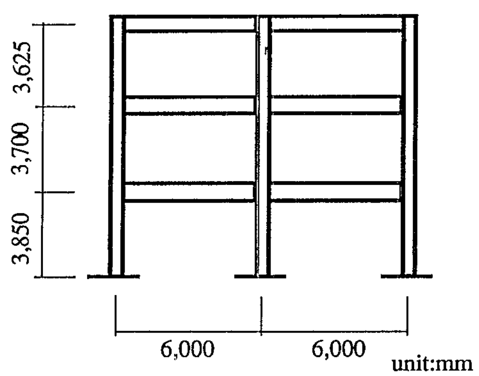

Fig. 4 Flow chart of this system

## METHOD FOR NUMERICAL STRESS ANALYSIS

The structures were composed with a member in that nodal forces were evaluated with actual experiment and members for that they were calculated by the numerical stress analysis. It is necessary to progress experiment and numerical stress analysis to perform the non-linear numerical stress analysis exactly with adjusting compatibility for forces and displacements among all members and for boundary conditions. The convergent calculations were performed by repeating the communication of data for nodal displacement and forces between a member that was under experiment and members for that numerical stress analysis evaluated them and by controlling the electric actuators until sum of nodal forces in the experimental member and in analytical members. It is necessary to perform numerical stress analysis for all the structure with including the experimental member to evaluate nodal displacements on them. We must assume the element stiffness matrix for the experimental members, as it was not possible to evaluate the element stiffness matrix for the experimental member in the plastic zone about the material characteristics. However, corrected displacements are overestimated excessively by underestimation of joint stiffness matrix, if assumed element stiffness matrix is lower than the actual element stiffness matrix for the experimental member. We decided to use the initial elastic element stiffness matrix for the experimental member to evaluate the higher element stiffness matrix in this study.

## STRUCTURE TO ADAPT THIS SYSTEM

We adapted this system to the pure steel frame structure that had three floors and two spans without any wall in Fig. 5. We also set up the left column at the first floor in the steel frame structure as an experimental member called a specimen. The configuration of an experimental member is shown in Fig. 6. We decided a reduced scale of the experimental member as one to ten by considering the capacity, the size and so on for test frame and equipment. The steel frame structure was selected as the adapted structure to verify this system, because it is clear to investigate the behaviors of the steel frame structure by using only numerical stress analysis in some certainty. The part (loading part) was set upper the experimental member to apply loading forces with electric actuators. The stiffness at the loading part was heightened by welding cover plates at the flange without occurring displacements when loading forces were applied. The test frame and the experimental member are shown in Photo. 1. Three electric actuators(two actuators in the horizontal direction and one in the vertical direction) were set up to apply the axial force, the shear force and bending moment combined freely at the top of column(experimental member). Electric actuators were supported and kept in space with four soft springs not to apply the unnecessary forces at the experimental member and load-cells, as weight of an actuator was about 80kgf.




| | |
|---|---|
| Columns | H-520×510×23×32 |
| Beams (2,3Floor) | H-700×250×12.5×19 |
| Beams (RF) | H-650×250×12.5×19 |

Fig. 5 Plane steel frame to adapt this system

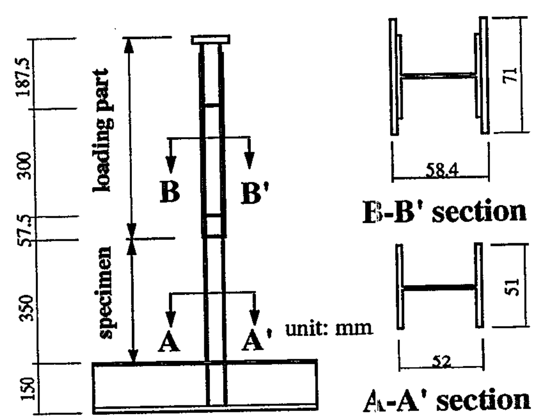



Fig. 6 Member to perform experiment

## DATA FOR LOADING FORCES

As it is possible to analyze the structures for arbitrary loading forces and designate displacement by using this system, we decided to apply horizontal forces that were pre-calculated and evaluated by using forces acquired from the earthquake for each time as followings.

(1) We evaluate the relations between a story shear and a relative story displacement for each floor by applying the static horizontal forces to the frame model shown in Fig. 7.

(2) The mass-spring model is evaluated with the frame model shown in Fig. 8.

(3) The dynamic analysis for this mass-spring model is performed by putting components for the north-south of the earthquake's wave at El Centro in 1940. The maximum acceleration of the input wave was enlarge to 450 cm/sec$^2$

(4) The horizontal forces at each time step are evaluated at each position of floors by subtract the story shear upper the required story from the story shear at each floor.

The hybrid and parallel experiment were performed with this system by using these horizontal forces varied at each time. The same experiment was performed by using horizontal displacements that were evaluated with the same method. Scale factors for the earthquake were reduced to one to hundred at the control with forces and to one to ten at the control with displacements, as the reduced scale of the experimental member was one-to-ten for the actual structure. Horizontal forces in the case of force control at each floor are shown in Fig. 9. This experiment was progressed at every 0.01 sec agreed with a time step at dynamic response analysis. The experiment was performed with applying about 380 data from 1.2 sec to 5 sec by neglecting small data for the beginning time.

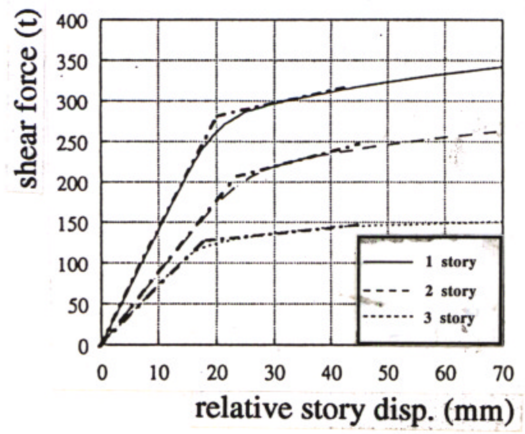
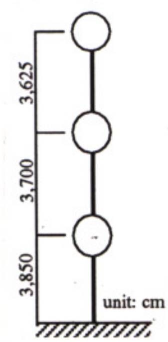



Fig. 7 Relation story shear and relative disp.




| story | mass (t) | 1st stiffness (t/cm) | 2nd stiffness (t/cm) | bending stiffness (tcm²) | yielded shear force (t) |
|---|---|---|---|---|---|
| 3 | 209.76 | 72.83 | 10.71 | $6.98\times10^{11}$ | 129 |
| 2 | 272.04 | 87.90 | 11.89 | $6.98\times10^{11}$ | 129 |
| 1 | 272.04 | 139.26 | 11.84 | $6.98\times10^{11}$ | 129 |

Fig. 8 Mass-Spring model

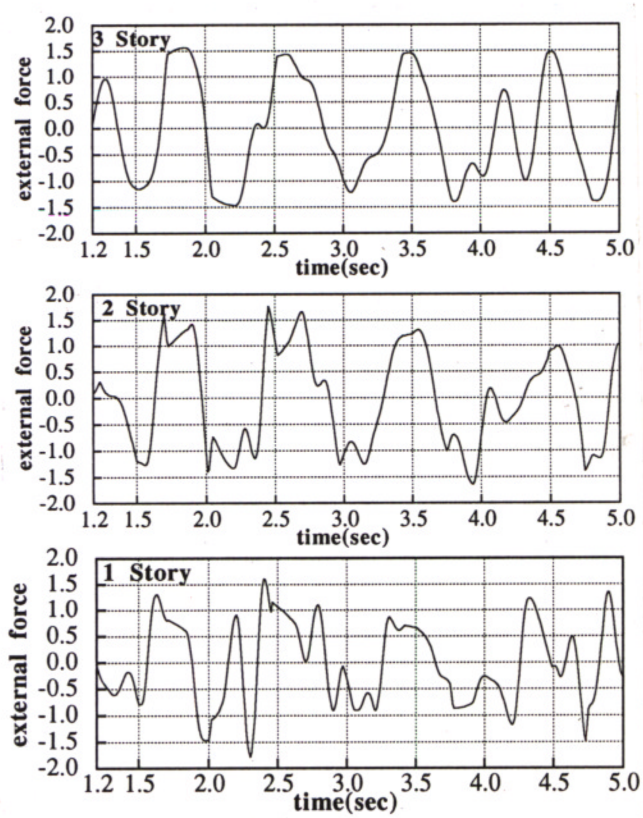



Fig. 9 External force to apply for each story
( load control)

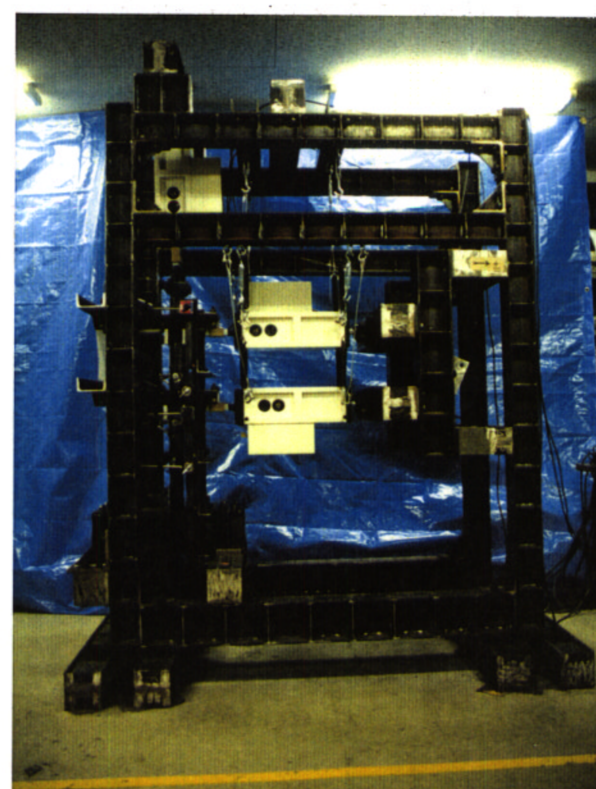


Photo. 1 Whole view of System

## RESULTS AND CONSIDERATION

### Story displacements and story shears at each step

Story displacements acquired with controlling forces at each step are shown in Fig. 10 and story shears with controlling displacements at each step are shown in Fig. 11. Single lines show the results with this system called Experimental and analytical system and dashed lines show the results by numerical stress analysis only. Both results by controlling forces were agreed with each other from 1.2 sec to 1.7 sec at the time step, as all members were in the range of elastic zones. Story displacements from this system were smaller than ones by the analysis only when some parts of member were yielded. It would be considered that second tangent modulus for the member in the analysis only, after members were yielded, was lower a little than ones in this system. Both results for story shear at each step in the numerical stress analysis and the results from this system were agreed with almost in the case of controlling displacements. The difference between the results with the numerical stress analysis only and the result by using this system in the controlling of displacement was smaller than the difference by controlling forces. It would be considered that influence from change of displacements to shears by controlling displacements was smaller than that from the change of shears to displacement by controlling shears as a reason.

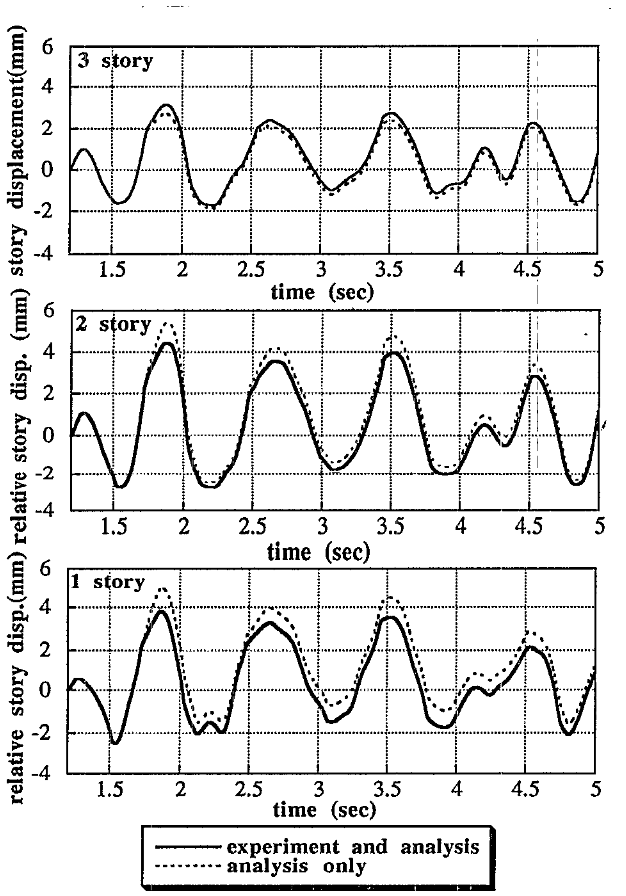



Fig. 10 Time history of relative story disp. ( load control)

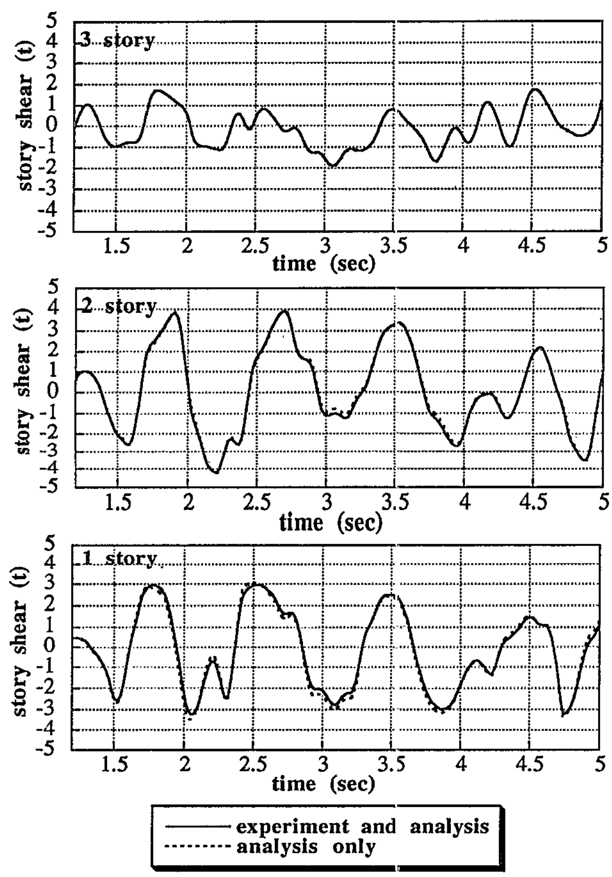



Fig. 11 Time history of story shear (disp. control)

Relation between story shears and displacements

The results for the relation between story shears and story displacements by controlling forces are shown in Fig. 12 and the results by controlling displacements are also shown in Fig. 13. Single line shows the results from this system and dashed line shows the results by numerical stress analysis only. Similar phenomena described in the previous section were recognized. It would be considered that same reason could be applied.

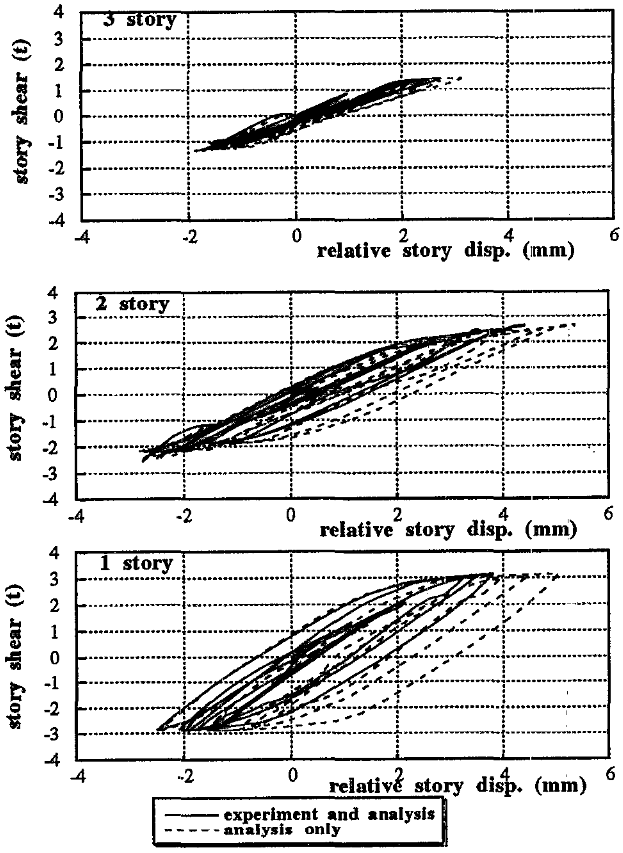



Fig. 12 Relation between story shear and relative story disp. (load control)

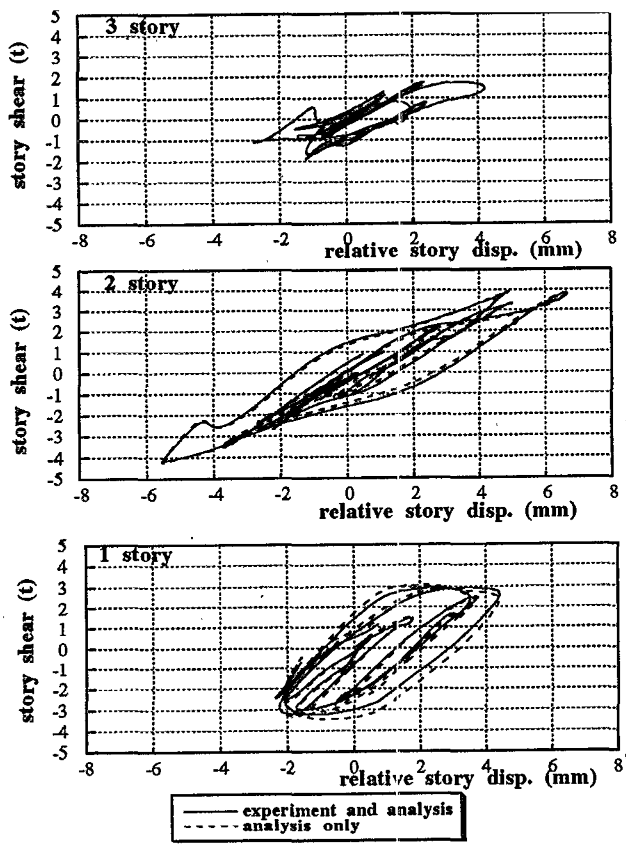



Fig. 13 Relation between story shear and relative story disp. (disp. control)

Change positions of inflection points for bending moments

The positions of inflection points for bending moments in the experimental member at each step are shown in Fig. 14. Single lines show the results by this system and dashed lines show the results by numerical stress analysis only. Thick dashed lines show the position of inflection point for bending moments with the static analysis by applying constant external force distribution. The results by this system show complicated change for the positions of inflection points according to changing external force distribution, though the positions of inflection points keep the constant value, even after some member in the structure varied from elastic zone to plastic zone. It is clear that it would be possible to investigate all complicated behaviors such as change of inflection points in the structure with this system by considering influence from change of inflection points.

Relation between axial force and shear

The relation between axial forces and shears in the experimental member by controlling forces are shown in Fig. 15. Single lines show the results acquired from this system and dashed lines show one by numerical stress analysis only. Thick dashed line shows the relation between axial forces and shears with static stress analysis under constant external force distribution. It is possible to control axial force only for this line as the target in the case of performing axial force in the traditional experiment for column members. It is clear that axial forces and shears with complicated change could be given on the experimental member by using this system.

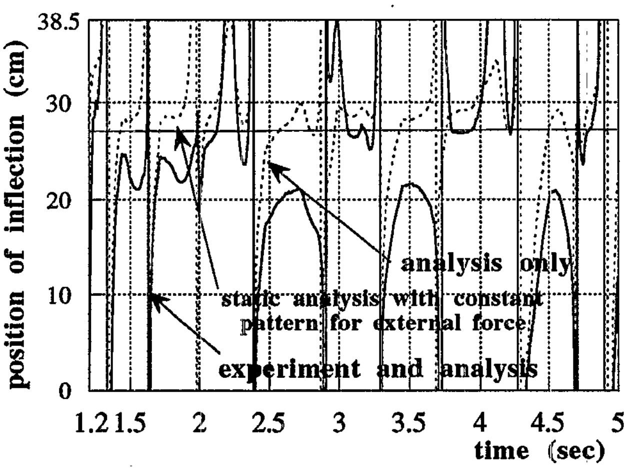



Fig. 14 Time history of inflection point with bending moment in a specimen (load control)

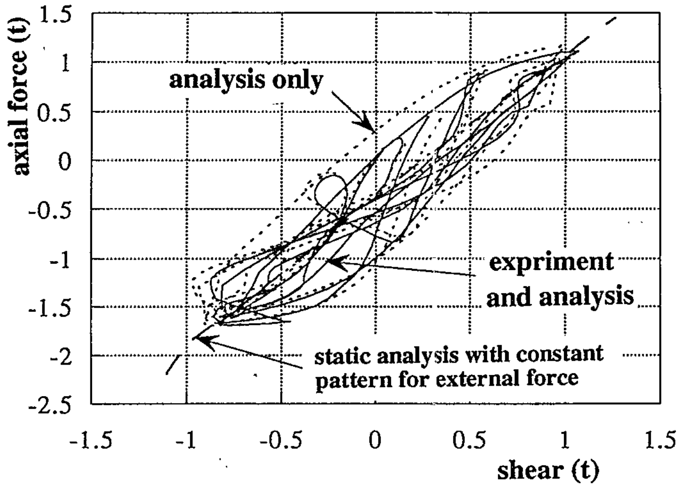



Fig. 15 Relation between axial force and story shear force in a specimen (load control)

## CONCLUSION

We developed a new experimental and analytical system to investigate behaviors even for non-linear fields in the structure by satisfying the compatibility for forces and displacement at the boundary parts between a member for experiment and other members for analysis in the structures. In this system, material characteristics, that are difficult to evaluate the numerical model, would be acquired from actual experiment and they are transferred in the structural analysis. We verified this system by adapting it to the steel frame with 3 floors and 2 spans. As it is necessary to improve the capabilities of electric actuators to bear against the high speed control, this system will be developed to more efficient system that can investigate all of behaviors in the structure as a whole.

## REFERENCE


M. Hakuno and M. Shidawara, (1969), "Dynamic Elapsed Experiment for Beam Controlling with Computer", *Proceedings of Society of Civil Engineers*, No.171, pp.1-9, (in Japanese)

K. Takanashi, K. Udagawa, M. Seki, T. Okada, H. Tanaka, (1975), "Non-Linear Earthquake Response Analysis of Structures by A Computer-Actuator On-Line System", *Transactions of Architectural Institute of JAPAN*, No.229, pp.77-83, (in Japanese)

M. Nakashima, M. Ishida, K. Ando, (1990),"Integration Techniques for Substructure Pseudo Dynamic Test", *Journal of Structural and Construction Engineering*, No.417,pp. 107-117, (in Japanese)

M. Fujimoto, A. Wada, K. Shirakata, R. Kosugi,(1973),"Study of Elastic-Plastic Analysis for Plane Steel Frame with Braces", *Transactions of Architectural Institute of JAPAN*, No.209, pp.41-51, (in Japanese)