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FUNDAMENTAL STUDY ON UNIFIED TOOL FOR STRUCTURAL ANALYSIS USING NETWORK

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SUMMARY

A lot of applications have been developed by many investigators, and have served for the precise analyses of member-buckling, local buckling, lateral buckling, and elasto-plastic behavior of various structural elements. But, as they have been used independently, we cannot analyze coupling effect of each phenomenon. In this point, we do not fully utilize present analytical applications. If we can unify these applications, various phenomena can be considered simultaneously in the analysis of whole building structure.

As the first step to realize above plan, this paper firstly proposes the simple method to transmit the numerical data through Internet. The elasto-plastic structural analysis of a steel braced frame is then conducted using several personal computers. Each computer analyzed composite beams, columns, and braces, respectively by using different applications. The stiffness-matrices of each member are transmitted to the host computer through Internet. Host computer constitutes the global stiffness-matrix for the whole structure, and solves the global stiffness-equation. The incremental deformations of each member are distributed to each computer from the host. Each computer analyzes the next step using the transferred deformations, and replies the revised stiffness to the host.

The results of the pushover analysis and the earthquake response analysis are shown. The deteriorating behavior of concrete in composite beams, and the post buckling behavior of braces can be simultaneously analyzed.

INTRODUCTION

When we analyze elasto-plastic behavior of steel building structures by using usual application such as CLAP.f [1], bending buckling of members and elasto-plastic behavior of joint panels can be considered. But lateral buckling of beams, local buckling of plates, composite effect of concrete slab on steel beams, etc. cannot be considered, and they are not in most conventional applications. Although the applications for the precise analyses of lateral buckling and local buckling have been developed [ex. 2, 3], the analytical objects are restricted to small structures because of the limited memory-size and CPU-

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performance. Concerning to composite beams, although precise analyses based on FEM were reported for the study of one beam, just simple and rough mechanical model was proposed for frame analyses [4].

As the applications for the precise analysis, such as lateral buckling, local buckling and composite beams, have been used independently, we cannot analyze the coupling effect of these phenomena. Plural unstable phenomena simultaneously occur in the stage of building collapsing. For example, when we analyze old buildings in which beams are not sufficiently supported and the plate elements are slender, we have to consider the coupling effect of lateral buckling and local buckling. In this sense, we can say that the present applications do not effectively utilized although a lot of good applications have been developed.

Recent improvement in the Internet technology is so successful that we can easily and quickly transmit a lot of information through Internet. If we unify the analytical applications developed by various investigators through Internet, we can analyze collapsing behavior and coupling behavior of various buckling so precisely in the analysis of whole building structures. Thereby, we propose unified system for structural analysis as follows; Plural personal computers (Stations) deal with the precise analysis of structural elements including unstable behavior. The stations correspond numerical information, such as stiffness, deformations, and restoring forces, with host personal computer that deals with the global constitutive equation. By transmitting information step by step, we can analyze precise behavior of whole building structures.

Using parallel processing and distributed processing, several projects on precise numerical structural analysis by connecting plural computers have been proposed [5-7]. They aim at high speed and big capacity in processing by the usage of plural computers. On the other hand, our project proposed here does not aim at gaining efficiency of processing, but aims at establishing highly precise analytical system by unifying present applications developed by various investigators.

Toward the final goal of unifying applications developed by various investigators, this paper deals with the structural analysis by unifying different applications developed by authors as the first step. For the steel frame with composite beams and braces, structural analysis is conducted with considering deteriorating characteristics of concrete and bending buckling of braces. Know-how obtained by this analysis will be utilized for the future analysis unifying applications for lateral buckling, local buckling, and so on.

SCHEME OF UNIFIED SYSTEM FOR STRUCTURAL ANALYSIS

Contents of transmitting data

Data flow in the unified system for structural analysis is as follows;
1) Each station constitutes initial stiffness matrix, and send the reduced stiffness matrix corresponding to boundary freedom to the host.
2) Host transfers the sent stiffness matrices to the global coordinates, and constitutes the global stiffness matrix by summing all matrices.
3) Host solves the global constitutive equation, and obtains incremental global displacements and restoring forces.
4) Host calculates the incremental deformations for each station by multiplying transfer-matrix to the incremental global displacements, and sends them to each station.
5) Each station analyzes the response for the next step, and sends the revised stiffness matrix to the host.
Step by step elasto-plastic analysis proceeds by repeating above procedures.

Data transmitted from the host to stations are the incremental deformations at boundary freedom. Data transmitted from the stations to host are the stiffness matrices corresponding to boundary freedom. In the present system, restoring forces at boundary freedom are included to the data transmitted from the stations to host in order to watch the equilibrium at boundary.

Following conditions and modification are necessary in order to utilize existing applications as the station in present system.
1) Responses for the given forced displacements should be calculated. As forced displacements are input from data file in general applications, the applications are easily coped with the unified system by modifying the input routine so that they obtain data from the host.
2) If the application is based on the matrix displacement method, as the stiffness matrix is already prepared, the transmitting stiffness matrix is just obtained by reducing it to the boundary freedom. When non-boundary (inner) freedom are many, it takes a lot of time for calculating the reduced matrix.
3) As the restoring forces at boundary freedom are generally calculated as responses, they can be just transmitted to the host.
As mentioned above, most of existing applications can be easily coped with the unified system by modifying only the input and output routine.

Host does not deal with all input data of analytical object. And output information obtained at each station is not gathered to the host. That means input data and output information is not included to the transmitted data. Input data for each structural part are to be input in each application based on respective format, and output information is to be output by each application based on respective format. This treatment needs the close collaboration among all operators of stations through the data input, execution, and study on results. It is beneficial for stations not to be black boxes.

Procedure of transmitting data

MPI libraries have been already developed and utilized for the parallel or distributed processing. Using these libraries, data can be quickly and stably transmitted among computers. But we need a lot of knowledge on information and communication engineering to use the libraries. It is so troublesome for structural engineers to use it. As we firstly aim at the collaboration with many structural engineers by unifying different kinds of applications, the development of extremely simple procedure for data transmitting is expected. Based on the standpoint that the first priority is given to the simplicity and the transmitting speed may be sacrificed to achieve the simplicity, we propose original transmitting procedure using file-sharing system prepared in the standard OS of personal computers, and using OPEN, CLOSE, READ, and WRITE commands in FORTRAN language.

Flow of transmitting data is shown in Fig. 1. Personal computers of host and stations mount the directory in file server using file-sharing system prepared in the OS. Sub-directories named “HOST” and “STATION” are prepared in the directory. The former is used for the data transmitted from host to station, and the latter is for the opposite direction. When we transmit data from host to station, host makes a text file by OPEN command, and writes data to be transmitted by WRITE command, and closes the file by CLOSE command. Then, station opens the file by OPEN command, and reads the data by READ command, and closes the file by CLOSE command. Thus, transmitting data from host to station is completed. If station attempts to read the file before it is made or it is under making, FORTRAN replies error messages. By preparing the error-resuming routine in which station repeats reading until error does not occur, the timing in communication can be achieved. These procedures can be described by using only the grammar of FORTRAN77. Host who made the communication file deletes it by himself. So, the permission of the directory “HOST” can be set that host can write and stations can only read. Such permission contributes the security of network. Similar procedure is applied when station sends data to host.

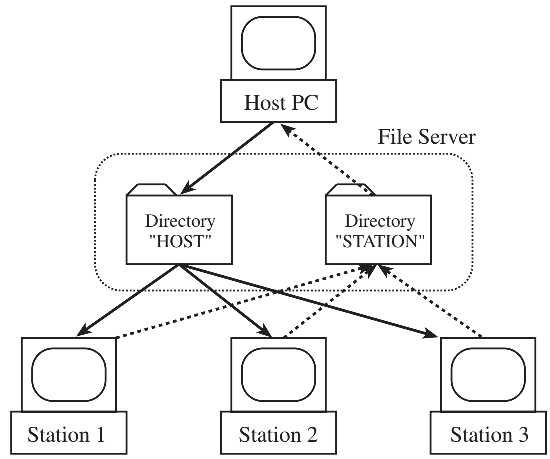


Fig. 1 Flow of Transmitting Data

In this paper, Windows® and Mac OS® are used as operating system (OS) of personal computers. When we mount the directory in file server using file-sharing system, SMB, AFP or WebDAV can be used as a connecting protocol. SMB is the protocol for Windows®, and AFP is for Mac OS®. WebDAV is a kind of HTTP protocol that is used for reading homepages. We have to overcome the problem concerning to firewall when we connect different LAN through Internet. Firewall is set to secure the LAN, and each LAN prohibits connecting some kinds of protocols based on respective policy. As SMB originally aims at the communication within LAN, almost all firewalls prohibit SMB to pass. WebDAV can pass almost all firewalls, provided the LAN permits reading outside homepages. It is because, WebDAV uses HTTP protocol, and connection can be achieved by the access from inside of LAN to outside. The defect of WebDAV is slow speed. It is about one third of others. In the analysis of present paper, the most suitable protocols were selected by considering above characteristics.

When we tried transmitting data between Osaka Univ. and Kumamoto Univ., the file that was read was the old file that should had been already deleted by the other. This problem comes from the cache. Because of cache, it takes some amount of time for the new files to be revised. In order to check if the file is the latest, sequential number is added to the communication file.

Characteristics of proposed system

Characteristics of proposed system are described as follows;

1) Collaboration of plural investigators can be achieved by unifying respective applications. The members of team can vary depending on the project.

2) Information to be offered among the members is just numerical data. We do not need to offer source codes nor libraries. That perfectly protects the right of the developers of applications.

3) It is so easy to participate the project because modifications only at input and output routine are necessary.

4) The procedure for communication through Internet is so simple, it just uses general file-sharing system and the grammar of FORTRAN77. But, the speed of communication is much slower than MPI library.

5) As one cannot grasp the behavior in other stations, the collaboration among all operators is necessary to study the analytical results. It is good for stations not to be black boxes.

TRIAL OF UNIFIED STRUCTURAL ANALYSIS

Analytical object

Analytical object is a steel building with 3 stories and 3 by 3 span as shown in Figs. 2 and 3. Diagonal braces are located in row A and D between row 2 and 3. Structural type is braced frame in X-direction, and moment resisting frame in Y-direction. Member sizes are selected depending on Japanese Building Standard Law.

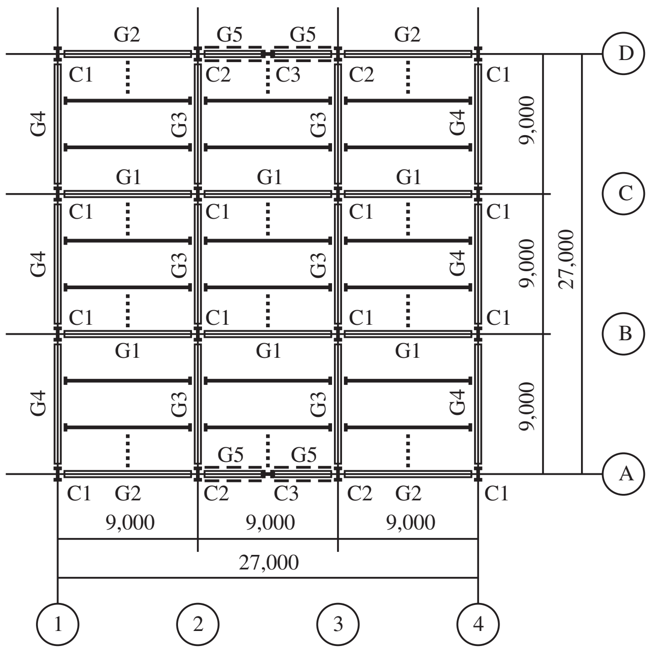
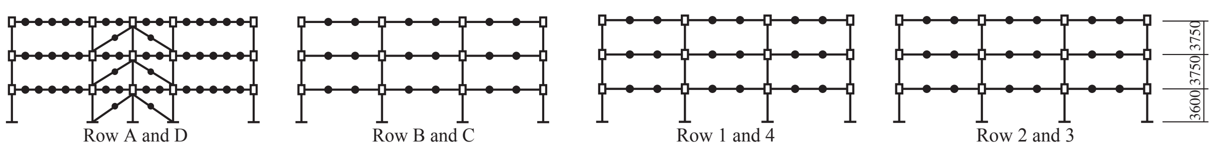


Fig. 2 Framing Plan of Analytical Object



(a) Frame in X-Direction (b) Frame in Y-Direction

Fig. 3 Frame Model for Analysis

Principal conditions in proportioning member sizes are as follows;

1) Dead load is 6,180 N/m^2 on roof, 4,710 N/m^2 on typical floor, and 2,940 N/m^2 for outer wall.

2) Live load for frame is 650 N/m^2 on roof and 1,800 N/m^2 on typical floor. Average live load for the whole floor of the story, which is used for the estimation of seismic load, is 300 N/m^2 on roof and 800 N/m^2 on typical floor.

3) Yield stress of steel is 325 N/mm^2.

4) Wide flanges with fictitious proportion are used for all members.

5) Width-to-depth ratio is 0.4 for beams, 0.7 for columns C1 and C2, 1.0 for columns C3 and braces. The minimum width of beams is set to 200 mm regardless of width-to-depth ratio.

6) Width-to-thickness ratio is 7.5 for beam flanges, 51 for beam webs, 8 for column flanges, and 37 for column webs. These values are the limitations for the most ductile members in Japanese Building Standard Law.

7) Sizes of sections are selected from discrete values of depth that is 50 mm pitch for beams, 25 mm pitch for columns, and 5 mm pitch for braces.

8) Composite effect of concrete slab on steel beam is simply considered in proportioning member sizes. Bending stiffness of the beam with slabs from both sides is 1.4 times the stiffness of steel beam, and the beam with slab from one side is 1.2 times. Composite effect on allowable and ultimate strength is ignored.
9) Vertical loads on beams in X-direction are modeled to 5 concentrated loads, and those in Y-direction are modeled to 2 concentrated loads.
10) Only two frames are analyzed using the symmetrical condition in both directions.
The member sizes proportioned are listed in Table 1. Here, doubler plates whose thickness is the same with column web are patched to joint panels in outer frames (row 1 and 4).

Table 1 Schedule of Member

Floor	G1	G2	G3	G4	G5
R	H - 350x200x 6.340x13.33	H - 300x200x 5.359x13.33	H - 550x220x 10.21x14.67	H - 450x200x 8.301x13.33	H - 300x200x 5.359x13.33
3	H - 300x200x 5.359x13.33	H - 300x200x 5.359x13.33	H - 600x240x 11.14x16.00	H - 500x200x 9.281x13.33	H - 300x200x 5.359x13.33
2	H - 300x200x 5.359x13.33	H - 300x200x 5.359x13.33	H - 600x240x 11.14x16.00	H - 550x220x 10.21x14.67	H - 550x220x 10.21x14.67

Story	C1	C2	C3	BR1
3	H - 475x332.5x 11.71x20.78	H - 475x332.5x 11.71x20.78	H - 175x175x 4.139x10.94	H - 150x150x 3.547x9.375
2	H - 475x332.5x 11.71x20.78	H - 475x332.5x 11.71x20.78	H - 225x225x 5.321x14.06	H - 185x185x 4.375x11.56
1	H - 500x350x 12.33x21.88	H - 500x350x 12.33x21.88	H - 275x275x 6.503x17.19	H - 200x200x 4.730x12.50

H – Depth x Width x Web thickness x Flange thickness

Constitution of host and stations

Constitution of personal computers for pushover analysis of braced frame in X-direction is shown in Table 2. Server machine in our laboratory of Osaka Univ. took a part of host, and dealt with the analyses of columns and joint panels, and controlled total behavior. Six all braces and three beams located at row A and B on roof and row B on the third floor were analyzed by cooperators in another organizations which are connected through Internet. Other beams were analyzed by personal computers located in LAN of our laboratory. The distribution of personal computers is shown in Fig. 4. Personal computers at total ten organizations were connected. OS and connecting protocols of all computers are shown in Table 2. On the other hand, personal computers only in LAN of our laboratory were used for the analysis of earthquake response analysis in X-direction and all analyses of Y-direction.

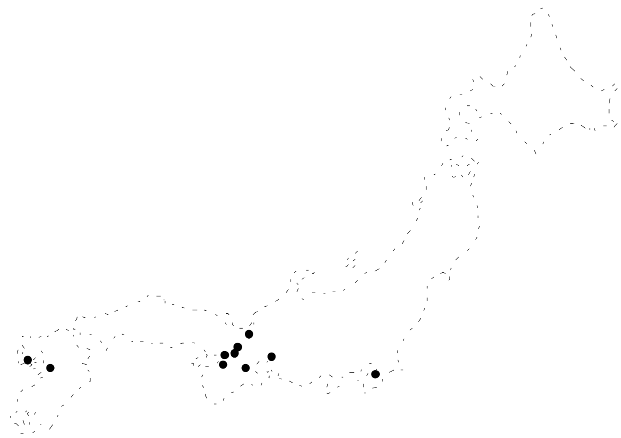


Fig.4 Distribution of Host and Stations

Table 2 Constitution of Personal Computers in Internet

Member		OS	Connecting Protocol	Organization
Host Column & Joint Panel		Mac OS® X Server v10.2	-	Osaka Univ.
Brace	Left at 3rd Story	Windows® XP	WebDAV	DPRI at Kyoto Univ.
	Right at 3rd Story	Windows® XP	WebDAV	Osaka City Univ.
	Left at 2nd Story	Mac OS® X	WebDAV	Kyoto Univ.
	Right at 2nd Story	Mac OS® X	WebDAV	Nippon Steel Co.
	Left at 1st Story	Mac OS® X	AFP	Fukui University of Technology
	Right at 1st Story	Mac OS® X	AFP	Kumamoto Univ.
Beam	Row A at Roof	Mac OS® X	AFP	Nagoya Univ.
	Row B at Roof	Mac OS® X	AFP	Nagasaki Institute of Applied Science
	Row A at 3rd Floor	Mac OS® X	AFP	Osaka Univ.
	Row B at 3rd Floor	Mac OS® X	AFP	Mie Univ.
	Row A at 2nd Floor	Windows® XP	SMB	Osaka Univ.
	Row B at 2nd Floor	Windows® 2000	SMB	Osaka Univ.

Outline of host program

Outline of program and mechanical models used in host are as follows;

1) Geometrical non-linearity is considered.

2) Interaction of bending moment and axial force is considered for the yield condition of columns. Generalized strain hardening yield hinge [8] is used as mechanical model after yielding.

3) Bilinear stress-strain relation with strain hardening ratio of 0.0001 is adopted.

4) Elastic shear deformation in columns is considered.

5) Shear deformation of beam-to-column joint panel is considered.

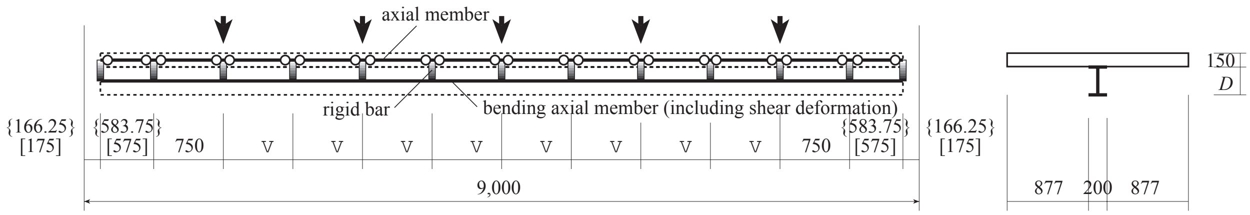
6) Bilinear relation in shear stress and shear strain is adopted. Yield shear stress is 250.2 N/mm^2 (which is the temporary allowable shear stress in the specification of Architectural Institute of Japan, AIJ), and strain-hardening ratio is 0.0001.

7) Horizontal displacements of adjacent nodes in parallel frames are equalized. Nodes in frames of X-direction whose horizontal displacements are equalized are A-1 and B-1 nodes, A-2 and B-2 nodes, A-3 and B-3 nodes, and A-4 and B-4 nodes. Nodes in frames of Y-direction are similar. The length of composite beam increases as the crack of concrete slab opens and closes. If horizontal displacements of all

nodes in the same floor are equalized, we cannot consider this characteristic. So, horizontal displacements of only adjacent nodes are equalized.

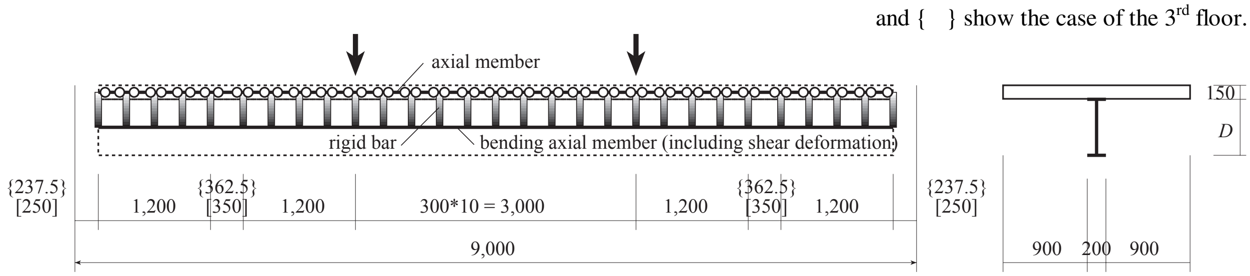
Outline of station program for the analysis of composite beams

Structural models for the analysis of composite beams that consist of concrete slab and steel beam are shown in Fig. 5. Steel beam is modeled to bending axial member including shear deformation, and concrete slab is modeled to axial member. These bars are located at the center of respective members. Assuming sufficient amount of headed studs are welded, slip between slab and upper flange of steel beam is ignored. So, bars of steel beams and those of concrete slab are discretely connected by rigid bars at some interval.



(a) Composite Beam in X-Direction

Figures in [ ] show the case of the 2nd floor
and { } show the case of the 3rd floor.



(b) Composite Beam in Y-Direction

Fig. 5 Structural Models for Composite Beams

As described later, deteriorating characteristics of concrete is modeled in the axial force-deformation relationship. When such deteriorating material is used, the length of elements affects the results. We have to set the length as the squash-region of concrete. In the present analysis, as the steel section in Y-direction is large, concrete slab will squash. According to the paper [9], the length of squash-region is almost twice of slab thickness. So, the unit length of concrete bars is set to 2×150 mm = 300 mm. On the other hand, the steel section in X-direction is so small that the steel beam yields and the concrete slab does not squash. For the sake of reduction in calculation load, rigid bars are arranged in sparse interval (750 mm).

For steel beams, interaction of bending moment and axial force is considered in yield condition. Generalized strain hardening yield hinge [8] is used as mechanical model after yielding. Bilinear stress-strain relation with strain hardening ratio of 0.0001 is adopted. Elastic shear deformation is considered.

For concrete slab, axial force-deformation relationship is set based on the stress-strain curve shown in Fig. 6. Effective width of concrete slab is calculated based on AIJ specification.

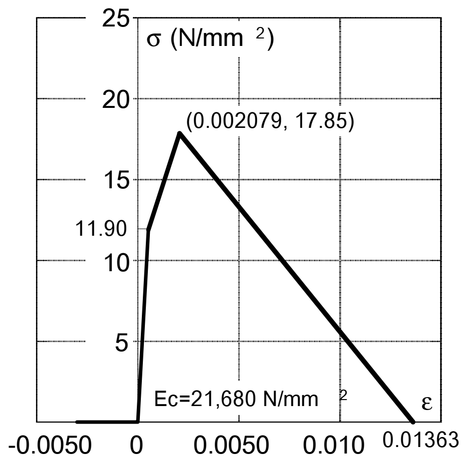


Fig.6 Stress-Strain Curve for Concrete

Boundary freedoms at which the substructure is mathematically connected to the host are horizontal, vertical, and rotational displacements at both ends, and also vertical displacements on which vertical loads are applied. This is because vertical vibration is considered in dynamic analysis, and also it is necessary in static analysis that one of these displacements should be selected as a control displacement in analyzing deteriorating behavior of concrete. Geometrical non-linearity is ignored in the analysis of composite beams.

Outline of station program for the analysis of braces

Structural model for the analysis of brace is shown in Fig. 7. Though braces can be included to the host program, they are separately treated because we want to get know-how of the distributed processing for deteriorating behavior caused by buckling. Mechanical model is the same with that of columns. A node is set at the mid of brace, and yielding is considered at the mid section and both ends. In order to express buckling behavior, initial imperfection whose amount is 1/1,000 of total length is considered, and geometrical non-linearity is strictly considered. Boundary freedoms to be mathematically connected to the host are not only rotations and elongation at both ends, but also the transverse displacement at the mid node (see Fig. 7). This is because we have to select the transverse displacement at mid node as a control displacement when the brace buckles in pushover analysis, and also we sometimes cannot get solution in earthquake response analysis [10] if we do not consider inertia force on the mid node when the brace buckles. Masses whose amount is the same with self-weight of half braces are considered at the mid nodes.

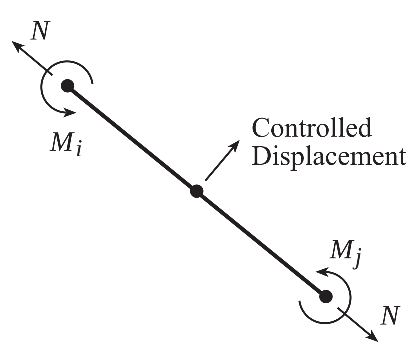


Fig. 7 Structural Model for Braces

Unified Analysis and Conventional Analysis

Proposed analysis in which sub-analyses of composite beams and braces are unified is defined as "unified analysis", and analysis by conventional application, CLAP.f [1], is defined as "conventional analysis". In conventional analysis, composite beams are dealt with that the bending stiffness is multiplied by 1.4 (for both slabs), and by 1.2 (for either slab) to the stiffness of steel beam, and composite effect on ultimate strength is ignored. Other analytical conditions are the same with unified analysis.

Fundamental periods of the building when vertical loads are applied are summarized in Table 3. Periods obtained by unified analyses are 0.548 sec for braced frames in X-direction, and 0.774 sec for moment resisting frames in Y-direction. Cracks of concrete slab are open at the ends of composite beams. Periods obtained by conventional analyses are 0.541 sec for X-direction, and 0.770 sec for Y-direction. The stiffness is little bit higher than that obtained by conventional analyses. In unified analysis, when horizontal forces are applied, crack at one end of composite beam closes, and the horizontal stiffness in unified analysis immediately becomes higher than that of conventional analysis.

Table 3 Fundamental Period

	X-direc.	Y-direc.
Unified analysis	0.548 sec	0.774 sec
Conventional analysis	0.541 sec	0.770 sec

Results of pushover analysis

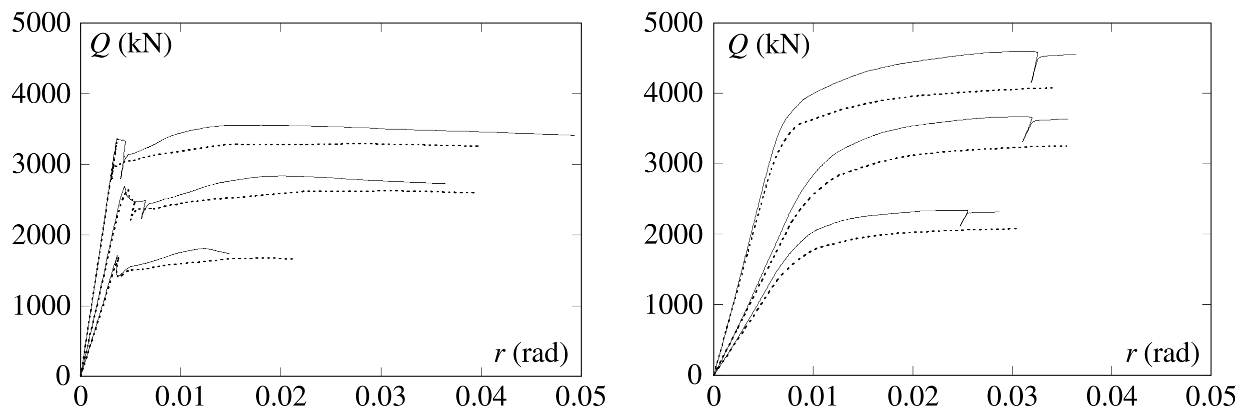
Results of pushover analyses are shown in Fig. 8. Horizontal forces are proportional to the seismic design forces stipulated in Japanese Building Standard Law. Figure (a) shows the case of braced frames in X-direction, and Figure (b) shows the case of moment resisting frames in Y-direction. Ordinate is story shear (Q), and abscissa is story angle (r). Three sets of lines corresponding to three stories are drawn. Solid lines show the results by unified analysis, and dotted lines show those by conventional analysis.

In the analyses of braced frame shown in (a), the sequence of brace buckling was 1st, 2nd, and 3rd story by unified analysis, while it was 2nd, 3rd, and 1st story by conventional analysis. Story shear and story angle reduce when braces buckle, and then increase again. This complicated behavior can be stably obtained by selecting transverse displacement of buckled brace as a control displacement.

In the analyses of moment resisting frame shown in (b), elastic stiffness of unified analysis (solid line) is higher than that of conventional analysis (dotted line). Although it is hard to recognize in this figure, initial stiffness near origin of dotted line is higher than that of solid line, and this relative relation immediately changes because of crack closing in concrete slabs. Horizontal strength obtained by unified analysis is larger than that by conventional analysis. This is because composite effect on strength is adequately considered in unified analysis by introducing structural models in Fig. 5, while it is ignored in conventional analysis.

Solid lines in Fig. 8 show small unloading just before the end of analysis. This is because of the deteriorating behavior by crushing of concrete slab in the composite beam at row A between rows 1 and 2 of the 2nd floor. Because the axial force in the slab deteriorates, we cannot find equilibrium path where story angle proceeds. In this unified analysis, post-crushing behavior can be stably obtained by selecting vertical downward displacement within the composite beam as control displacement. When axial force in the slab reaches zero, Q and r turn to increase, while the controlled downward displacement keeps increasing.

Total number of steps was 613, and duration time was 120 minutes for the unified pushover analysis of braced frames in X-direction, while the duration of conventional analysis was only 1.5 minutes. As the composite beams are precisely modeled in unified analysis while they are simply modeled as single bars in conventional analysis, we cannot directly compare them. But it can be said that we have to sacrifice the speed of analysis in our unified analysis system. In this point, we insist that our first aim is the collaboration of different kinds of applications, and is not improving efficiency of processing. For the sake of the first aim, slow but extremely simple communication is preferable. We are now trying to collaborate with complicated buckling analyses. In this trial, as it needs a few minutes of CPU time for one step, disadvantage of time for communication is negligible compared to total duration time.



(a) Braced Frame in X-Direction (b) Moment Resisting Frame in Y-Direction

Fig. 8 Story Shear – Story Angle Relation in Pushover Analysis

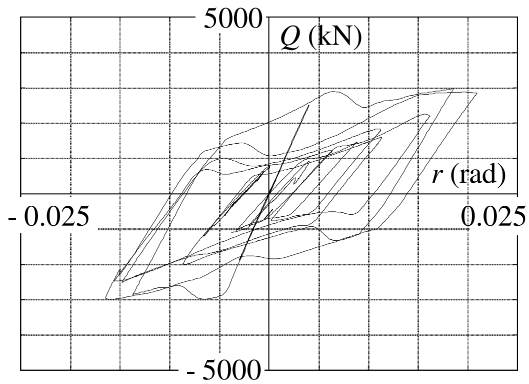
Results of earthquake response analysis

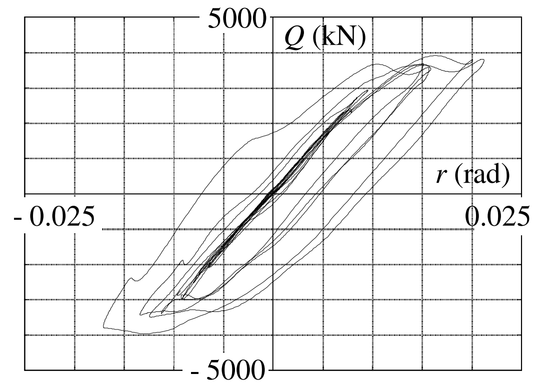
Dynamic analyses for El Centro NS with 100 cm/sec of the maximum velocity were conducted. Viscous damping proportional to the initial elastic stiffness is adopted, with the coefficient of damping as 0.02 for the first vibration mode. Duration of forced motion is 10 sec.

Relations between story shear (Q) and story angle (r) are shown in Fig. 9. Figure (a) shows the case of braced frames in X-direction, and Figure (b) shows the case of moment resisting frames in Y-direction. Ordinate is story shear (Q), and abscissa is story angle (r). In Fig. (a), Initial Q-r loops are large and gradually become small, which is the typical characteristics of braced frames.

Figure 10 shows the relation between bending moment (M_L) and rotation (θ_L) at A-end of the composite beam (between rows A and B at row 1 of the 2nd floor). Dotted line in the figure shows the relation obtained by static pushover analysis. Deteriorating behavior can be recognized in large deformation of dotted line that is caused by crushing of concrete slab. In the first quadrant, dynamic M_L-θ_L relation shows the loading behavior keeping the moment value at full plastic value of steel section, and then stiffness and moment again increase after crack of concrete slab closes. This is the typical behavior of composite beams [4]. Figure 11 shows the relation between axial force (N) and axial deformation (δ) of the left brace at the 2nd story. We can recognize typical behavior of buckling strut.

We can conduct dynamic earthquake response analysis in which characteristics of composite beams and braces can be expressed by proposed unified structural analysis.





(a) Braced Frame in X-Direction (b) Moment Resisting Frame in Y-Direction

Fig. 9 Story Shear-Story Angle Relation in Earthquake Response Analysis

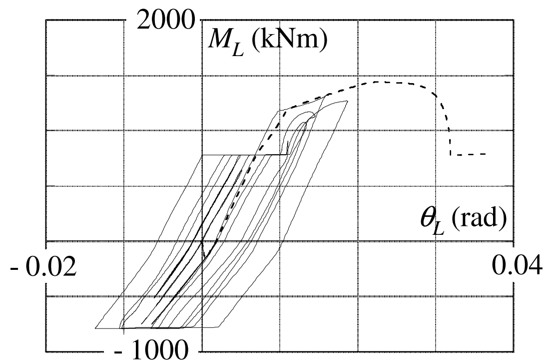


Fig. 10 Moment-Rotation Relation for Composite Beam

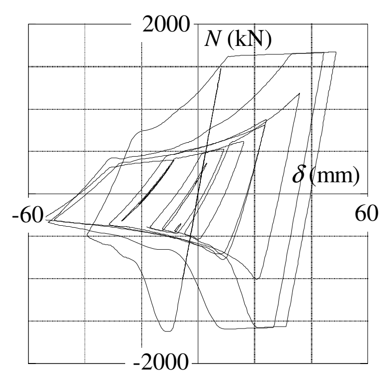


Fig. 11 Axial Force-Deformation Relation for Brace

CONCLUSIONS

We proposed the analytical system in which various kinds of applications are unified through Internet in order to analyze various deteriorating behavior. As the first step to realize proposing system, three story steel building that consists of composite beams and braces was analyzed by combining plural applications through Internet. Major conclusions are summarized as follows;

1) Original transmitting data procedure through Internet using file-sharing system prepared in the standard OS of personal computers, and commands of FORTRAN77 was proposed.

2) Deteriorating behavior can be stably analyzed by adequately selecting boundary freedom between host and station.
3) Example of unified analysis in which 13 personal computers in 10 organizations are connected through Internet, was successfully conducted.

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