U.S.-JAPAN COOPERATIVE EARTHQUAKE ENGINEERING RESEARCH PROGRAM ON COMPOSITE AND HYBRID STRUCTURES - JAPANESE SIDE RESEARCH ACCOMPLISHMENTS -

by

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ABSTRACT

The U.S.-Japan Cooperative Earthquake Engineering Research on Composite and Hybrid Structures initiated from 1993 fiscal as a five-year research project. Many research results obtained in this project have been presented in many technical papers. This paper summarizes the general objectives and the results of this project and makes clear the position of each technical output.

KEY WORDS: Composite and Hybrid Structures; Concrete Filled Steel Tube Column System; RC Column and Steel Beam System; RC Core Wall with Exterior Steel Frame System; and New Materials, Elements and Systems.

1. INTRODUCTION

Recently, "composite and hybrid structures" which uses the different material in the right man for job is very generally told in the world of research and development. However, it is the actuality that it is very slow on the gait of the popularization in the business world. This is a result of basing on there being no design code recognized [1].

In the Building Research Institute - Ministry of Construction, the basic examination was carried out through the research on beam-column connection of the composite and hybrid structures which makes the beam to be steel structure and the column to be reinforced concrete construction from 1985 [2, 3]. Then, the U.S.-Japan Cooperative Earthquake Engineering Research on Composite and Hybrid Structures [4] was started by the five-year project from 1993. The research operation system is shown in Figure 1. Domestic cooperative research by the Building Research Institute, the Building Contractors Society, the Japan Structural Consultants Association, the Kozai Club, and the Building Center of Japan was organized with the research collaboration from the universities. Research adjustment with the U.S. side was carried out by the Technical Coordinating Committee and the Technical Sub-Committees, which synthetically adjusted the research content.

There is a purpose of the research for making clear how to evaluate the composite and hybrid structures in general, but not handling individual composite and hybrid structures. However, the concrete research goal is a pile in the length, even if it goes with that the composite and hybrid structures in which the limitless variation is possible is generally handled from the research beginning. Therefore, both Japan and

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program started in 1993 in Japan and in 1995 in the U.S. The two year time lag is being taken as an opportunity to plan the future research work in a more careful and useful manner in order to derive the most benefit from the work that has already been completed on both sides. The overall coordination efforts, cooperation and exchange of information have been excellent. More active exchange of research personnel is currently occurring in this program. At least four or five researchers from each side have participated for short and long term durations.

More details on the current status and technical progress made in this program can be found in the minutes of the last (fifth) JTCC meeting (Ref. 2). A listing of the general recommendations from that meeting is given in the Appendix of this paper. A www site has also been established which contains updated information on the overall status of this program as well as summary of results and findings from individual research projects (www.eerc.berkeley.edu/usjchs).

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2. "Summary, Resolutions and Recommendations of the Fifth Joint Technical Coordinating Committee Meeting," Report No. UMCEE 98-43, Department of Civil and Environmental Engineering, The University of Michigan, Ann Arbor, MI, 48109-2125, December 1998.

APPENDIX

General Recommendations from the 5th JTCC meeting:

1. Exchange of researchers, and research data (e.g., via www) on both sides should be continued at an increased level.

2. Close cooperation and collaborative research effort on both sides should be continued till the end of the five year program of both countries.

3. Efforts to synthesize and interpret knowledge gained in the program, and to disseminate this knowledge and design/analysis methodologies to the design profession and industry should be accelerated.

4. Planning effort should be initiated to perform testing work on carefully selected full frames in possible cooperation with other research programs.

5. Material manufacturers, construction and other industrial organizations should continue to actively support the research program.

6. Each JTSC should meet as needed to achieve good coherence in the cooperative research work.

7. Each JTSC should continue development of performance criteria as related to design guidelines to be developed in each country.

8. Funding should be provided for joint coordinated publication of research work with practical implications.

9. The 6th JTCC meeting should be held in late summer of 1999 at a place to be hosted by the U.S. side.

U.S. selected the any concrete structures in which the interest together had, and the research for these was advanced. If there is common part in the aseismic designing method of which each structure is proposed, they should be synthesized. By equipping 4 sub-committees of the structures using concrete filled steel tube column system, RC column and steel beam system, RC core wall with exterior steel frame system, and new materials, elements and systems, the research was advanced.

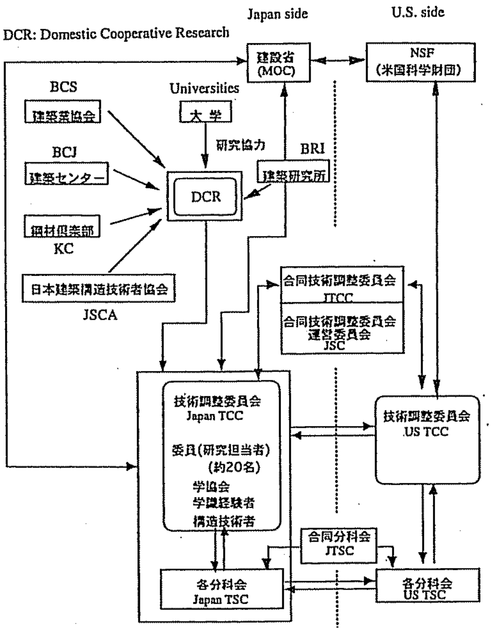

Figure 1. Research Operation System

In the U.S. side, 2 years will continue the research in future, since the start of the research was retarded a little, thus, the information exchange of research result between U.S. and Japan is continued. In this report, the outline of the technical result of every structural form of concretely selecting research result [5, 6, 7, 8, 9] in the Japan side is reported, because provisional settlement was carried out by 1997 fiscal, and it summarizes whole result of this study.

2. CLASSIFICATION OF COMPOSITE AND HYBRID STRUCTURES

It is possible to classify the composite and hybrid structures into three structural forms, as it is shown in Figure 2. Each classification is correspondent to one-dimensional, two-dimensional and three-dimensional composite and hybrid structures.

The first classification is the composite and hybrid member. Single member such as beam and column has been composed of the different material in this classification. It is considered that the SRC member is typical example of this classification. Both CFT member and fiber reinforced concrete member enter this category.

The second classification is the composite and hybrid frame. Even if the individual members such as beam and column are not special, by combining these becomes the composite and hybrid structure. RC column and steel beam system is in this category.

The third classification is the structure that different materials and members were combined three-dimensional. Typical example of this classification is the RC core wall with exterior steel frame system, and RC frame in the lower stories with steel frame in the upper stories is in this category.

Three structures of CFT, RCS and HWS selected in this study as concrete research objects are positioning of choosing for exemplification like as representative player of each classification of composite and hybrid structure forms. Therefore, it is considered that the research may be advanced by the process equal to this study, when other composite and hybrid structure of identical classification will be examined in future. On the structures of these three, the practical application had already been made in the part, and the research was advanced with the aim of the development of design guidelines, which had the generalization in mind.

In addition to 3 classification of the above, the RFI research positively making use of new materials, members and systems non-usable in the architectural field at present is being promoted parallel, because the variation of the composite and hybrid structures may be rapidly expanded. On this research, the research was advanced in the mid-and-long viewpoint with the aim of the storage of basic technical information.

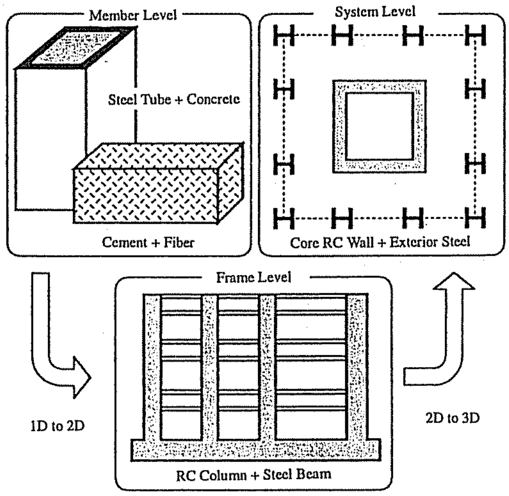

Figure 2. 3 Classification of Composite and Hybrid Structures

3. CONCRETE FILLED STEEL TUBE COLUMN SYSTEM

The CFT structure is handled at the SRC Standard of Architectural Institute of Japan [10] as a kind of SRC. However, it becomes the handling of the special structure on the Building Standard Law for the reason that the requirement of concrete cover thickness for steel tube is not satisfied. A quantitative grasp of improved strength and ductility by the synergetic action between concrete and steel tube, investigation of mixture of concrete and placement, and improvement in the fireproof performance by filling concrete was done by New Urban Housing Project. However, left examination subjects are as follows: the more exact examination of the synergetic action between filled concrete and steel tube, the applicability to larger diameter-thickness (width-thickness) ratio (152 for circular section and 74 for square section), the applicability to high strength materials (20 ~ 90MPa for concrete and 270~850MPa for steel tube), the effect of variation of axial force (between 0.3 of tensile yield force and 0.7 of compressive yield force), the effect of the direction of seismic force (45 and 22.5 degrees in loading direction), and the structural performance of beam-column connection. Then, the examination by experiment and analysis was carried out on these problems in this study. From the viewpoint of the design business, various plan and number of stories were designed, and the rational application method of the CFT system was also examined.

(A) Short column central compression experiment,
(B) Short column eccentricity compression experiment,
(C) Beam-column experiment,
(D) Beam-column connection experiment, and
(E) Examination by the trial design.

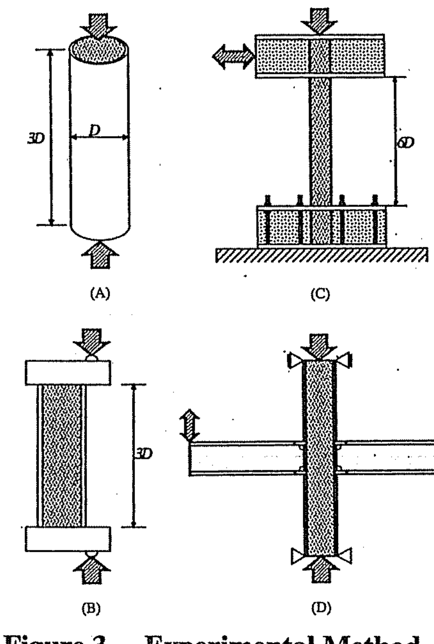

Figure 3. Experimental Method

Got conclusions are arranged as follows. More detailed explanation of the conclusions is written in the reference [6].

(1) There was a clear scale effect, when performance of structure was examined by the experiment on CFT column of larger cross section (450mm in outer width for square section and 323mm in outer diameter for circular section) than that of standard test specimen handled in past. Therefore, the strength formula considering synergistic effect must be corrected a little in the downward.
(2) As a result of the more detailed examination considering the scale effect got in (1), it was proven that the confinement effect for filled concrete could not be included.
(3) The stress-strain model of steel tube which receives circumferential stress and that of the concrete which receives the tri-axial restraint were proposed. The calculated bending moment-curvature relation of the cross section from the stress-strain model for steel tube and concrete agreed well with the experimental result.
(4) It was shown that to balance the material strength between steel tube and filled concrete was important. Especially in the case of using high strength concrete, the steel tube is relatively weak, the confinement by steel tube is not possible.
(5) It was possible to evaluate the elasto-plastic behavior of the column which receives the combined bending and shear by using stress-strain model proposed in (3), when the appropriate plastic hinge region was assumed. However, since the calculation is complicated, the restoring force characteristics were evaluated as empirical formula using post-yield rigidity and deformability from past experimental result from the practical view point, while the strength was calculated from proposed stress-strain model. This proposal is also fundamentally possible on the application to the high strength material.
(6) On the behavior of beam-column connection, systematic examination were not carried out. This study verified that the conventionally proposed strength formula can evaluate the strength safely and can be applied to high strength materials.

4. RC COLUMN AND STEEL BEAM SYSTEM

In the RCS system, the flow of the force between steel beam and RC column was a problem to be dealing with. It was Tominaga et. al. [11] who gave the practical solution for this problem first, in which the method for restricting the connection by the similar approach to the CFT system was proposed. As this system is quite rational to buildings which has long beam span with small number of stories like the shopping center, many construction companies originally proposed beam-column connection reinforcement method and the performance verification experiment is carried out. These are achieved over 20 types of connection details, even if they are classified very roughly. Like this, as the knowledge on the RCS system is accumulated to some extent, to arrange and generalize past technical information was made to be the goal in this study.

To begin with, past test data was collected, and the database was constructed. In the meantime, the details of mainly existing beam-column connection was classified into the through column type and through beam type. The additional experiment was carried out on each of the insufficient part. Studies on the exterior column to beam connection, the effect of floor slab, the column top to beam connection, the 3 dimensional column to beam connection under 2 directional seismic force, and the frame behavior were newly carried out, which were generally not required in the structure examination in the past. FEM analysis was also carried out thanks to the rapid advance on the elasto-plastic finite element method and the feasibility of 3 dimensional beam-column connection by advance of the capacity of the computer. It becomes the following, when research item is enumerated.

(A) Construction of the database and the examination of strength formula.
(B) Examination on the stress transfer mechanism.
(C) Effects of various reinforcement methods of the through beam connections.
(D) Effects of various reinforcement methods of the through column connections.
(E) Strength evaluation of the exterior column to beam connection.
(F) Behavior of the 3 dimensional beam-column connection.
(G) Elasto-plastic behavior of the frame.
(H) Examination of the reliability of the elasto-plastic finite element analysis.
(I) Examination by the trial design.

The obtained conclusions are summarized as follows. It is well-informed in the reference [7].

(1) The database was constructed on past 436 test data. According to this database, evaluation accuracy of various existing strength calculation formulas (shear strength, bearing strength).
(2) Based on the database constructed in (1), the evaluation of the shear behavior of beam-column connection was proposed.
(3) From the experiments and analyses on the exterior column to beam connection and column top to beam connection, the shape factor of the beam-column connection showed being approximate to 3:2.4:1.4 relation.
(4) From 2 directional loading testing on the 3 dimensional beam-column connections, the phenomenon in which the restoring force characteristics of beam-column connection repeatedly deteriorated was observed. However, it was also proven that the contrary good performance in the viewpoint of the energy absorption was shown.
(5) Frame experiment of the 2 story with 2 spans was carried out, and the effect of the yielding in the panel-zone on the restoring force characteristics of the frame was examined. Through the analysis by the elasto-plastic finite element analysis, it was confirmed to be estimable in respect of the micro stress state and macroscopic deformation in and around the beam-column connection, which showed the applicability of finite element analysis method for future business application.
(6) Whether the design of beam-column connection was practically possible by the trial design was examined for the building of 6 and 12 stories.
(7) Transfer mechanism of bending moment and shear force from steel beam to RC column was newly proposed from the basic experiments.

5. RC CORE WAAL WITH EXTERIOR STEEL FRAME SYSTEM

HWS system is the structure in which the structural elements are clearly sharing the role to resist external / internal force, that is, the core RC wall is made to bear most of the seismic force, while the external steel frame bears only the vertical load. In the region where the earthquake does not become a problem like the east coast region in U.S., the structure of this type spreads as a generalized technology, however on the earthquake performance, there are many indefinite points. Then, the examination of the ideal way of earthquakeresistant design of such structure was made to be a goal of this study.

It is possible to design the RC wall as a clear bending yield type. It is self-evident that the deformability of bending yield type wall is very large. However, Ds=0.4 was required even in the minimum in the current Building Standard Law. So, the main examination object was: how far demand strength is reduced actually, and how each element should be designed.

The first problem is the stress transmission in the junction. The steel beam fundamentally supports only the vertical load, and the steel beam end which connects the core RC wall and the exterior steel frame is made to be the pin connection. It is necessary to examine whether the beam end satisfies the actual pin condition.

The inertial force must be transmitted through the slab as shear, because most horizontal force is borne in RC wall of the center core. The shear force is transmitted to the exterior frame at the first floor level, when there is the underground stories, and in the underground, the reverse shear force seems to work. It is necessary to examine how to deal with these. This point is the second issue to be examined.

The third is how to deal with large axial force produced in the edge of the wall by large overturning moment. The placement of the much reinforcements is required in the wall in order to deal with this axial force, and after all, it becomes a reason of bringing about the non-ductile behavior in the earthquake resisting wall. It is also necessary to examine that the yielding of coupling beam which connects RC walls gives what kind of effect in the structural performance of the overall structure.

Then, lateral loading test (Photo 1) of 12 storied coupled shear wall was carried out by 1/3 scales in this study. Through this research, the detailed examination of the exchange of the shear force between two walls through the coupling beam was carried out. From the becomingness of the earthquake resisting wall to be 3 dimensional, L- and T-shape walls received the axial force fluctuation and the shear span ratio fluctuation. The examination of the behavior in receiving these effect was carried out.

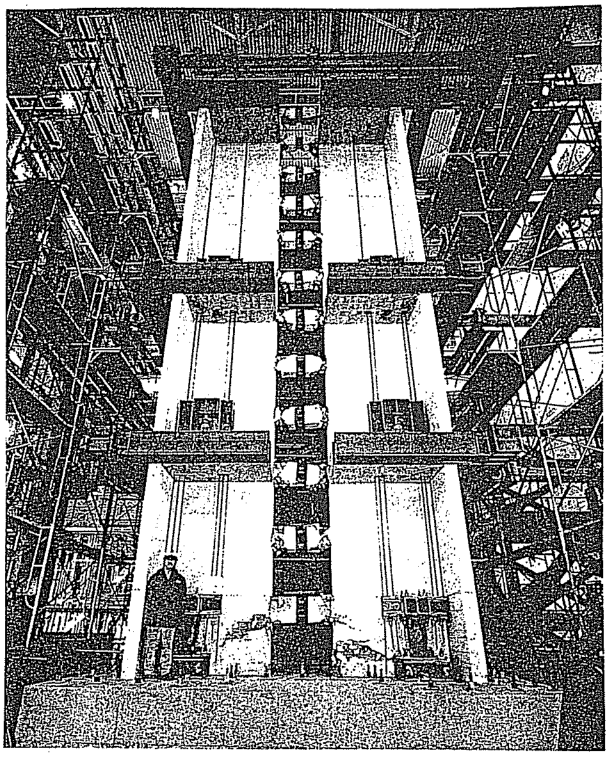

Photo 1. 12-Storied Coupled Shear Wall Test

The outline of the research result [8] on this structure is shown in the following.

(1) From experiment and analysis on the coupled shear wall of 12 story, it was shown that there was wedge action by the coupling beam, which produces concentration of the shear force in the compression. This will give basic information on the shear design of shear wall. This result did not contradict the study result in Canterbury University and Univ. of California, Berkeley carried out in the past.

(2) From the experiment of T- and L-shape walls, the effect of the fluctuation axial force, the effect of the bending moment gradient, the confinement effect at the edge of the wall under 2 directional seismic force were evaluated.
(3) The evaluation method of restoring force characteristics of the RC coupling beam reinforced diagonally was proposed from past research data.
(4) The recommended details on the joining method between steel beam and core RC wall was proposed.
(5) The 12 storied HWS building was designed, and it made clear the problems in carrying out the practical design. The seismic designing method which put the base on the equivalent linearlization method was proposed, here, the damping characteristics of shear wall and coupling beam were properly evaluated.

6. NEW MATERIALS, ELEMENTS AND SYSTEMS

Remarkably the variation of the structural system expands, if newly available materials are applied in the list of the building construction material. Therefore, in this study [9], the feasibility study on the usability of some selected materials from various fields was carried out. As the result, continuous fiber reinforced concrete and high-performance cement-based materials were made to be an examination object.

On continuous fiber reinforced concrete, the utilization to the plate elements, the application to strengthening of existing RC members, and the use for electrical facilities were examined. Since the need of application to strengthening of RC members after Hyogo-ken Nanbu Earthquake, the research rapidly developed unexpectedly. The practical research on the application to column with side wall and beam with spandrel wall was carried out.

In the meantime, on high-performance cement-based materials, realization of light-weight high strength and high ductility were aimed at.

In the light-weight high strength study, 30 MPa in strength with specific gravity of 1.2 and 60 MPa in strength with specific gravity of 1.6 were made to be a target to be developed.

These concrete materials were developed in this study, and the problems which brought about when applying the design technique of conventional RC member to the member made of these concrete materials were investigated.

On high ductility, improvement of tension and compression ductility further than the conventional concrete by mixing the short fiber into the cement was studied, which is expected to be used in the damage control portion of the structure. Types, aspect ratios, mix amount and water to binding material ratio of the short fiber were varied based on the approach of the fracture mechanics. It was confirmed that the strain hardening characteristics which is rich in ductility is obtained, and some structural tests were carried out. The examination from the practical design viewpoint was carried out on the relation between material ductility and the performance of the structural element.

Further research is in need in the RFI research field.

7. SUMMARY

By the revision of the Building Standard Law (June 12th, 1998), the seismic design by new verification method became possible together with the conventional prescribed design method. In the new verification method, the constraint by the structural form is not received, if the structural performance is confirmed to satisfy the goal performance. Therefore, it will be possible to usefully use a technical knowledge on the structural performance of the composite and hybrid structures variously got in this study in the application of the new verification method.

The conventional prescribed design method is also reviewed with the revision of the Building Standard Law. Based on the technical storage by this study, CFT system and RCS system are under the examination of handling in the prescribed design method. HWS system is the most ideal structural system which may be examined by the new verification method. The result obtained in this study is utilized to develop the new verification method in detail. The mid-and-long term result is expected on the RFI system. However, the research progress is unexpectedly advanced on carbon fiber sheet wrapping method for RC member, which is under the process of developing design guidelines.

It is regret that the integrated seismic design method, which can cover composite and hybrid structures in general, could not be proposed in this study. However, the result is steadily being utilized for generalization. We consider that this study will give some incentive to those who plan to research and develop new composite and hybrid structural systems.

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