U.S.-Japan Cooperative Earthquake Engineering Research Program on Composite and Hybrid Structures
- Japan side Progress -

by

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ABSTRACT

The composite and hybrid structural research project [1] is being carried out in Japan and the U.S. cooperatively under the UJNR Panel on Wind and Seismic Effects. In Japan, the research started from 1993 fiscal as a five year project under the co-sponsorship of the Ministry of Construction and private sectors such as the Building Contractors Society, the Kozai Club, the Building Center of Japan and the Japan Structural Consultants Association, which constitute domestic cooperative research (Chairman: Prof. H. Aoyama, Nihon Univ.). In this research program, four types of composite and hybrid structure systems are selected and investigated. Three of them are more practical and aimed at developing design guidelines, which are concrete-filled steel tube column system (CFT), reinforced concrete column and steel beam system (RCS) and concrete core wall with exterior steel frame system (HWS). The last one is a research on new materials, elements and systems (RFI) which might be used combined with traditional structural counterparts in composite and hybrid structures in future. This report will summarize the research progress on these four research topics.

Key Words:
Concrete-Filled Steel Tube,
RC Column with Steel Beam,
Core Wall with Exterior Steel Frame,
New Materials, Elements and Systems

1. RESEARCH ON CFT

1.1 Basic Research Plan

There are many experimental and analytical studies on CFT systems which are reported in technical journals. First, the strength and ductility of the CFT systems are predicted by processing these existing data. Secondly, the effectiveness of these predictions will be verified by supplementary experimental studies. As the materials' strengths in use are quickly increasing recently, wide range of structural steel strength and concrete strength are considered to verify the applicability of the predictions.

1.2 Research Items And Its Progress

(1) Experimental and Analytical Study

The objectives of the experimental study are to evaluate the synergistic effects of structural steel tube and filled concrete and to evaluate stress transfer mechanisms in beam-to-column connections. So as to clarify these problems, the following experiments are planned with several study parameters.

a) Experiments
   1) stub-column tests
   2) stub-column eccentric loading tests
   3) beam-column tests
   4) beam-to-column connection tests

b) Study Parameters
   1) tube shapes (rectangular, circular)
   2) tube strengths (400, 600, 800 MPa)
   3) width-to-thickness ratio (FA, FC, FD-rank* 1)
   4) concrete strengths (20, 40, 80-90 MPa)
   5) connection details (diaphragm, etc.)

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Ninety stub-column tests on rectangular or circular sections were already completed. As the dimensions of the selected specimens are relatively large, and material strengths of structural steel tube and concrete are also large, the maximum test strength reached 1,400 tonf. As for the stub-column eccentric loading tests, sixty specimens have been completed.

From the comparison between these test results with sectional analyses, the stress versus strain models for concrete infill and steel tube are proposed.

As for the beam-column tests, 20 rectangular and 12 circular specimens were tested. Most of the specimens (16 for rectangular and 8 for circular sections) were tested under the constant axial thrust of 40% of yield strength and others (4 specimens each for rectangular and circular sections) were tested under varying axial thrust of 70% of yield strength in compression and 30% in tension. The structural steel strengths (400, 600, 800MPa), concrete strengths (40, 90MPa) and width-to-thickness ratios (FA, FC-rank) were selected as test parameters. As for rectangular sections, 4 specimens were loaded in the direction of the plane which inclined 22.5 or 45 degrees from their principal axes. Fairly good agreements both in restoring force and axial shortening characteristics are obtained between test results and analytical ones, in which the proposed model for stress versus strain relationships for concrete and steel tube are adopted. 3D-FEM analyses were also conducted to see the stress diagram in the CFT beam-columns.

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*1 FA-rank of width-to-thickness ratio means that large member ductility is expected thanks to its compact section. FC-rank means that it can at least assure the yield strength of the member without deterioration. The width-to-thickness ratio of FD-rank is chosen as 1.5 times of that of FC-rank.

Ten beam-to-column connection specimens are now under fabrication. Nine of them are one-way frame specimens (seven of them will be tested with constant column axial force and two will be tested with varying axial force) and the rest is the two-way frame specimen.

Ten additional stub-column eccentric loading specimens are also under fabrication, which are planned to evaluate the moment versus axial force diagram of CFT section loaded in the direction of the 45 degrees from the principal axes.

(2) Empirical Study on Ductility

The analytical evaluation of the ductility of beam-columns looks not promising. Therefore, the empirical formulation for the ductility of beam-columns was tried both for rectangular and circular sections using test results in this project and the existing test results. Empirical formula taking into account the factors of axial force, width-to-thickness ratio of steel tube and concrete infill strength were proposed for rectangular and circular sections. The calculated ductilities are compared with test results in good agreement especially with test results completed in this project.

(3) Theme Structure Study

Structural designs of 10, 24 and 40 storied CFT moment frame buildings and CFT dual system buildings were carried out. In these structural design, CFT member strengths were calculated based on the simple (generalized) superposing method proposed in the AIJ-SRC standards [2]. The buildings with the same plan were also designed as pure steel frames. The total amount of structural steel, which is the index for estimating the economy of buildings, used for CFT buildings was compared with that used for pure steel buildings. In this comparison, CFT showed advantages over pure steel especially for higher buildings. The economical difference in CFT buildings with/without bracings was not large. It was because that the weight of bracings and the weight increase in the braced bay frame members compensate with the weight reduction of other frames which carry less horizontal force.

Above consideration was conducted on the original theme structure which has 32 columns in each story. The modified plans which have 16 or 24 columns in each story, which were expected to show more advantages by CFT columns, were also investigated. The detailed comparison of these plans will be carried out in future.

2. RESEARCH ON RCS

2.1 General

In Japan, a great number of beam-to-column sub-assemblage tests on RCS systems have been conducted. However, most of them are just proof tests to verify the performance of the sub-assemblages which were designed as weak beam systems. Therefore, these test results gives us little information on the shear strength and ductility of the beam-to-column joint panels in the ultimate stage.

Therefore, the experimental study in this research project is planned to obtain the ultimate strength and ductility of the beam-to-column joint panels by making the specimens to be intentionally weak in panels.

2.2 Research Items And Its Progress

(1) Literature Survey - Database

Experimental database was made, in which the information of the load versus displacement relationships is just included as the turning point information such as peak strength and peak displacement etc. but not as a whole curve. The collection of about 400 test data was completed at present and will be maintained (added) in each year.

The following investigation is underway on the collected database: (1) pick up test data which failed in shear of joint panel, (2) classify them in details and geometry, and (3) compare their strengths with existing shear strength formula. Better design formula are expected to be proposed through this study.

(2) Beam-To-Column Connection

a) Stress Transfer Mechanism Study

The shear strength of the joint panel is thought to be the sum of the shear strengths of inner concrete, outer concrete, structural steel and hoops. The contribution of outer concrete is questionable as it is not known how the shear stress is transferred from inner part. So as to make clear the stress transfer mechanism, several sophisticated experiments were carried out. The test results clearly showed the existence of such shear transfer mechanism.

b) Through Column Type Joint Tests

Ten specimens for interior beam-to-column connections were tested. In these tests, the effects of vertical stiffeners and the cover plates were investigated.

c) T- and L-Shaped Joint Tests

Fifteen beam-to-column connection specimens were tested to make clear the effects of the geometries (cruciform, T and L) of the joints. Here, the joint details of the through beam type with FBP, cover plate and band plate are all included. The through column type is also considered. Through these experiments and 3D-FEM analyses, the shape factors for cruciform shaped joint, T-shaped one and L-shaped one are preliminary proposed as 0.30, 0.24 and 0.14, respectively.

d) 3D-FEM Analyses

Elastic and inelastic characteristics of bond and friction between concrete and steel were investigated by basic experiments. The test results were reflected to modify the 3D-FEM program. Eighteen case studies were carried out. The analytically obtained monotonic load versus deflection relationships were compared with the envelops of the cyclic behaviors with good agreement, which verified the effectiveness of 3D-FEM analyses. The 3D-FEM analyses gave us better understanding of the stress distribution in the beam-to-column connection.

e) 3D Joint Tests

So as to see the inelastic behavior of beam-to-column connections under two directional loading, four 3D specimens were constructed. Three of them are through column type and one is through beam type. The test will soon start at BRI and will continue about two months.

(3) Frame Test

So as to understand the overall inelastic behavior and required ductility in each structural elements of RCS frame, a two story (1.35m in story height) and two bay (2.1m in beam span) frame specimen is planned. The frame is designed to be weak panel.

(4) Theme Structure Study

Six- and twelve-storied theme structures were designed, and static and dynamic analyses were conducted. In these theme structure study, the beam-to-column connections were assumed to be elastic. The dynamic analyses were conducted simplifying the frame into lumped mass model. These study gives us the general characteristics of the RCS frames. So as to see the local ductility of RCS frame, the inelastic dynamic frame analyses are planned.

3. RESEARCH ON HWS

3.1 General

The structural system of core wall with exterior steel frame is not common in Japan and its design method is not established yet. So, six, twelve and twenty-four storied theme structures were preliminary designed. According to the preliminary design, six storied model was considered to be designed just depending on the large shear strength of walls. Twenty-four storied model needed hat truss (and belt truss) to reduce large overturning moment induced at the foot of the coupled shear walls, which made the development of general design procedure rather difficult. Therefore, twelve storied theme structure was first selected and the design problem was picked up. Then, the design implication will be expanded into much higher or lower systems. The rationality of the designed system will be verified through the analytical and experimental studies.

3.2 Research Items And Its Progress

(1) Coupled-Shear Wall Test

One-third scale model of 12 storied coupled-shear wall test was carried out. During the test, the forces acting in each member was measured so as to understand the force re-distribution in the coupled-shear walls and boundary beams for design purpose. For this purpose, load cells were installed into all boundary beams. The coupled-shear walls showed very stable hysteresis loops until 1/67 radian in drift index. From the readings of the load cells, it was observed that the boundary beams act like wedges inserted between walls after they crack and expand in length. These test results are under investigation by FEM and MS (multi spring) model analyses.

(2) T- and L-Shape Shear Wall Test

So as to understand the stiffness, strength and deformability of 3D-wall is essential for the design implication to HWS systems. Three one-third scale T-shaped shear wall specimens without boundary columns, which represent the walls of the lowest story of the 12 storied prototype HWS system, were conducted. In these tests, the shear force and flexural moment with different moment-to-shear ratios were applied with varying axial forces.

Large axial force is expected at the corner of the 3D-wall of lowest story when two directional seismic force affects the HWS system. Then, the ductility of the corner part of the wall depends much on its confinement. Therefore, four L-shaped shear walls varying their confinement level were tested with large axial force. These test data are utilized to develop hysteresis model of 3D-walls.

(3) Literature Survey

About eighty papers on boundary beams and thirty papers on RC wall to steel beam connections were surveyed. As for the inelastic behavior of the boundary beams, the past analytical and experimental information can be considered to be enough for design purpose. On the other hand as for the RC wall to steel beam connections, the isolated joint strength tests can only be found in the reports and no sub-assemblage tests are found. From this viewpoint, some verification test may be necessary for RC wall to steel beam connection. However, as the flexural stiffness of the steel beam with long span is very small and the rotational deformability of the joint itself is not so large, the experiment is not considered.

(4) Theme Structure Study

First, twelve story model building was designed on the basis of the general Japanese design concept. The strength of the designed building was too large to be investigated as the target structure to be developed. Then, the building was revised considering the design concept for the coupled-shear wall in New Zealand [3]. In New Zealand practice, earthquake load is distributed to each wall according to the overturning moment ratio carried by boundary beams. As the building still had large overstrength, the reinforcements in the core walls were intentionally reduced to reach reasonable strength level, 35 percent of the base shear coefficient. The final building is investigated whether it performs well or not under the seismic effects through the dynamic inelastic analyses using fish-bone model or frame model.

4. RESEARCH ON RFI

The following two research groups for " Fiber reinforced plastic (FRP) elements" and " High performance concrete (HPC)" are organized.

4.1 FRP Research

The research program on effective utilization of FRP materials for composite and hybrid structures contains three research items as follows. These items were selected through the feasibility study on effective utilization of FRP.

a) Development of the evaluation method for high-performance FRP-RC panels.

b) Development of the effective repair and/or strengthening method by using FRP for existing RC members.

c) Feasibility study on the effective utilization of FRP to the electrical facilities.

As for the former two items, various types of element tests are underway so as to understand the basic reinforcing characteristics of FRP. As for the last item, electrical problems brought about by using steel reinforcing bars in electrical facilities were identified and the electrical characteristics of FRP were also understood from the literature survey.

4.2 HPC Research Plan

There are few cooperative research between concrete makers and structural designers in Japan. The makers have many technologies but they don't know how to use it. On the other hands, designers have a few information about new technologies of concrete. But they have many hints about the idea of future concrete.

The main objective is to exchange the information of makers and structural designers to discuss about how to use effectively the concrete materials to the structural members and how will be the future concrete. Through the discussions, the following two topics are depicted.

a) Development of ultra light weight and high strength concrete.

b) Development of high tensile strength and high ductility concrete.

As for the light weight concrete, two kinds of concrete which have 1.2 in specific gravity and 30 MPa in strength, and 1.6 in specific gravity and 60 MPa in strength were realized and several fundamental tests on bond strength and compressive strength are on the way.

As for the high tensile strength concrete, various types of fibers with mortal were tested and some of them showed high tensile strength and good compressive ductility. However, it was made clear that the such performance is quite sensitive to the kind of fibers. The investigation will continue.

5. SUMMARY

The Japan side research progress was presented. The five year project is now the final stage in Japan, so the formulation of practical design guidelines are just initiated.

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