# EXPERIMENTAL STUDY ON THE PERFORMANCE OF THE RC RESEARCH ON NEW MATERIALS, ELEMENTS AND SYSTEMS

**Subhash C GOEL[1], Atsuo TANAKA[2], Hiroyuki YAMANOUCHI[3] And Hiroshi FUKUYAMA[4]**


## SUMMARY

This paper presents a brief summary of research work carried out in both countries on developing and application of new and advanced materials for use in innovative composite structural elements and systems (Research For Innovation - RFI) under the US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures. Thus, the studies in this group are more of feasibility type than those in the other three groups, Concrete filled tube composite system, RC column – steel beam composite system and RC core wall – steel frame composite system, where the objectives are to develop detailed guidelines for practical design work. The research work includes Fiber Reinforced Plastics (FRP), and High Performance Concretes (HPC). Utilization of FRP materials has been studied in RC-FRP panels, repair and strengthening of existing RC members by FRP, and use of FRP in electrical facilities. Light weight concretes with specific gravity of 1.2 to 1.6 and compressive strength of 30 to 60 MPa, and advanced cementitious composites with ultra ductile behavior are under development. A few innovative composite systems consisting of steel and fiber reinforced concrete (FRC) have also been studied. In these systems, the structural elements are made of selective combinations of FRC and steel members. The combinations under study include: FRC-encased open web steel joists, and high performance FRC core encased in slurry infiltrated mat concrete (SIMCON) shells for reinforcement as well as stay-in-place form work. Studies on selective use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in critical elements and regions of composite structures, such as joints and connections of precast elements, have produced excellent results.


## INTRODUCTION

In order to meet various social demands for building structures, which nowadays becomes higher and higher, development of performance based structural engineering has been underway in major countries. One of possible answers for this trend is to aggressively utilize new/advanced materials for building structures. The objective of the Research For Innovation (RFI) studies under the US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures is to clarify the feasibility of structural elements and systems that can use effectively new/advanced materials targeting higher levels of structural performance than that required by current codes. To achieve this purpose, interactive research activities between a material phase (material design and development) and structural phase (structural analysis, test and evaluation) are strongly needed. In other words, the most significant recognition for research is to make 'feed back and forth' cyclic procedures to reach final goals of new structural systems with new/advanced materials that has not yet been used for building structures so far.

On the basis of the above thought, the RFI studies divided into three steps as shown in Fig. 1; material level, element level, and system level. The research on materials includes basic tests for material properties and development of constitutive models for analysis. The 2nd step, research on elements, includes structural test and FEM analyses utilizing the developed constitutive models of material. The last step, research on system, includes


[1] *Dept. of Civil and Environmental Engineering, The University of Michigan, U.S.A. Email: subhash@engin.umich.edu*
[2] *Dept. of Architecture, Faculty of Engineering, Utsunomiya University, Japan Email: tanakaa@cc.utsunomiya-u.ac.jp*
[3] *General, Building Research Institute, Ministry of Construction, Tsukuba, Japan E-mail: yamanoch@kenken.go.jp*
[4] *IISEE, Building Research Institute, Ministry of Construction, Tsukuba, Japan Email: fukuyama@kenken.go.jp*

dynamic response analysis of structures based on the study on elements, and finally development of design guidelines. In each step as well as between steps, 'feed back and forth' cycles were given to gain better solutions in terms of performance. Every research on RFI was conducted based on this framework in order to meet various social demands for building structures under the performance-based engineering.

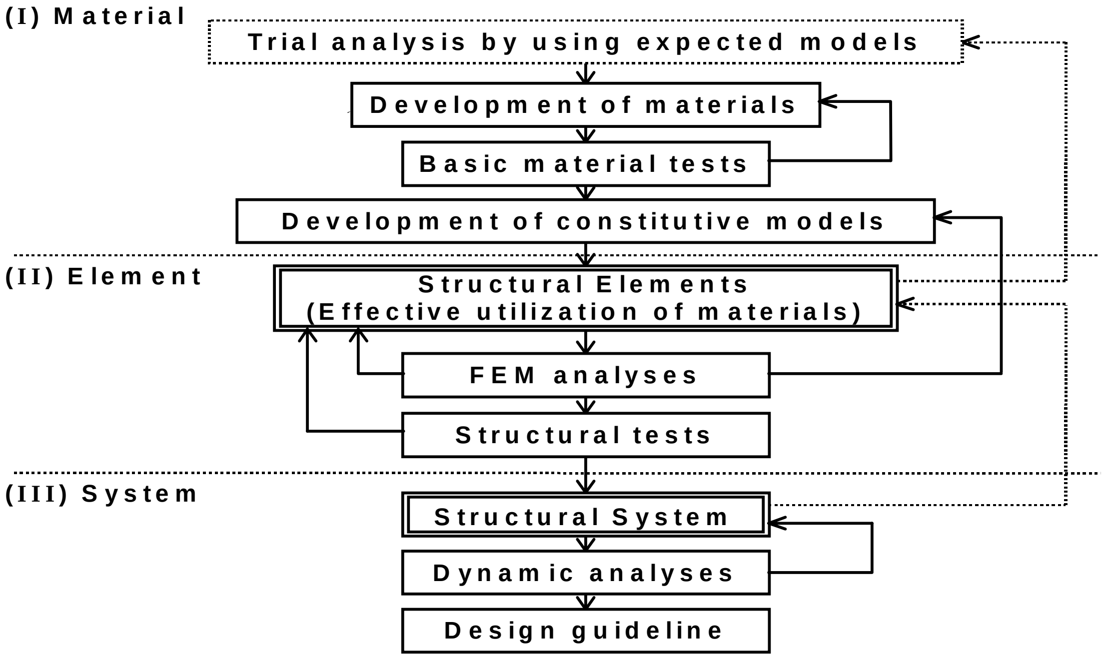


**Figure 1: Framework of RFI**

## JAPAN SIDE PROGRAM

The topics covered in the Japanese side research projects include: (a) Effective utilization of Fiber Reinforced Plastic (FRP) materials for innovative composite structures, such as High performance FRP mesh reinforced mortar panels, Seismic retrofit of RC members by fiber composite sheets, and Effective utilization of FRP to meet the electric or electromagnetic requirements, (b) Development innovative structural systems using High Performance Concrete (HPC), such as Ultra Light Weight Concrete and Ductile Engineered Cementitious Composites. FRP, HPC, Intelligent material, Prestressed steel member, Hinge device, Mega-structure system, Recyclable element, Fireproofing material for CFT, and High-performance steel were discussed as possible topics in the feasibility study conducted in the first fiscal year (1993) of the US-Japan Cooperative Earthquake Research Program. Hearing type meetings with material manufacturers and general contractors were conducted from a view of the feasibility that above items to be research topics of RFI. Through this study, FRP and HPC were selected as research items of main studies. A brief description of the individual projects is given in the following:

### High performance FRP mesh reinforced mortar panels

(P.I. - S. Fujii, Kyoto University and T. Kanakubo, Tsukuba University)

FRP has unique properties like high resistant to corrosion, high strength, lightweight and non-magnetism. Flat and tube type FRP mesh reinforced mortar (FRP-RM) panels are focused on to use as forms and concrete filled tube elements, respectively. Both innovative elements are expected to increase building performances caused by the unique properties of FRP. Objective of this research is to study the upgrading effect in structural performance of these innovative composite elements with FRP-RM panel. Constitutive models of FRP-RM panel elements for FEM analysis were discussed through the tests on axial tension and in-plane shear of FRP-RM composite materials. Evaluation methods for the structural performance of innovative composite elements were investigated by the tests of concrete elements with FRP-RM composites under axial compression loading and lateral loading. The concrete filled FRP-RM tube columns and the RC beams with FRP-RM envelope were effective to enhance not only shear capacity but also ductility and durability of RC elements. Thus, the feasibility of the FRP-RM composite elements for performance upgrading was clarified.

**Seismic retrofit of RC members by fiber composite sheets**

(P.I. - Y. Matsuzaki, Science University of Tokyo and H. Fukuyama, Building Research Institute)

Objective of this research project is to develop evaluation methods for structural performance of retrofitted RC members by fiber composite sheets (FCSs). Targeted RC members for retrofit are existing members designed according to the previous codes or damaged members by an earthquake. The FCSs wrapping method, wrapping fiber sheets around RC members with resin as shear reinforcements, was used in this study. This is one of the new technologies for seismic retrofit developed in Japan. The special feature of FCSs as light weight, high resistant to corrosion, high strength and flexibility and so on, deals with many advantages in structural performance, durability, construction work, cost of the retrofitted structures. This method was already applied in many retrofitting construction works because of its excellent efficiency. The most important advantage of this method for building user is that the FCSs wrapping method can satisfy the strong social demand, the buildings can be operated during the retrofitting construction. However, no codes for retrofit design and construction utilizing the FCSs wrapping method were proposed in the building engineering area in Japan.

Shear capacity and ductility of retrofitted RC rectangular beams, T-shaped beams (beams with slab), square columns, columns with non-structural walls, and shear walls with FCSs were investigated experimentally. Shear capacity of retrofitted RC members with round bar as longitudinal reinforcement, flexural upgrading of beams and slabs, and shear capacity of RC retrofitted columns without removal of finishing etc. were also discussed. Through these investigation, design guidelines includes testing methods of the composite materials, structural design concept and methods for the retrofitted RC members were proposed.

**Effective utilization of FRP materials to meet the electric or electromagnetic requirements**

(P.I. - H. Fukuyama, Building Research Institute and Y. Matsuzaki, Science University of Tokyo)

Objective of this item is to propose the solution methods of electricity-related problems arising from the use of steel reinforcement. It seems that use of steel reinforcement causes a number of electricity-related problems. For example, electrolytic corrosion of steel reinforcement often occurs at the sites in the vicinity of power plants, transformer stations or electrical equipment for ordinary buildings. In addition, adverse effects of stray currents, leakage currents and electromagnetic waves on computers, electric facilities and other sensitive equipment in ordinary buildings are not uncommon. Although guide ways of high-speed transportation system driven by linear motors, atomic power plant by nuclear fusion and electric power storage by super-conduction will become reality in a not-so-distant future, use of steel reinforcement is impossible since the electric currents in steel reinforcement will affect the magnetic fields. Therefore, it is highly possible that FRP reinforcement will be used in areas where use of steel reinforcement poses problems. Extracted the electricity-related problems arising from the use of steel bar and the solution methods for these problems using FRP materials were obtained through the study.

**Performance evaluation of RC elements with ultra light weight concrete**

(P.I. - K. Kobayashi, Fukui University, H. Fukuyama, Building Research Institute, S. Hakuto, Tokyu Construction Co. Ltd., T. Toritani, Toda Corporation and H. Kumagai, Shimizu Corporation)

The advantage of utilizing ultra light weight concrete is to decrease the seismic forces occurred in the structures and the sustained load of foundation due to the weight of superstructures. Construction cost due to transportation will also be reduced. The main objective in this research project is to propose a performance evaluation method of RC structural elements with ultra light weight concrete for structural design.

Uniaxial compression test of confined concrete by tie-hoops, bond splitting test of beam elements, flexural/shear test of beam elements, lateral loading test of shear walls and fire resistant test of beams under loading were conducted. Two types of ultra light weight concrete were developed for the tests. The one was 1.2 in density, 30 MPa in compressive strength and the other was 1.6 in density, 60 MPa in strength. The normal weight concrete with 30 and 60 MPa in compressive strength were also used in the tests as control. These test results indicated that the shear and bond splitting capacities of the RC elements with ultra light weight concrete are lower than that with normal concrete. Cracking pattern was also different between the structural elements with light weight concrete and normal concrete. On the other hand, fire resistance of the light weight concrete beams exhibit almost the same performance with that of conventional RC beams. The cause of the differences was investigated by analysis of the test results and design methods for flexure, shear and bond splitting are proposed by using the adequate modification of the conventional evaluation equations.

**Ductile Engineered Cementitious Composite Elements for Seismic Structural Applications**

(P.I. - H. Fukuyama, Building Research Institute and Y. Matsuzaki, Science University of Tokyo)

A collaborative effort between US and Japanese researchers focuses on an innovative seismic resistant structural system utilizing Engineered Cementitious Composite (ECC) elements. The main objective in this research is to obtain high level of building structural performances in safety, reparability and serviceability. The ECC, which exhibits excellent properties in ductility and damage tolerance, employed in this research is Polyvinyl Alcohol (PVA) fiber reinforced mortar designed using micromechanical concepts [Li and Leung, 1992]. The ultra ductile behavior of ECC combined with its flexible processing requirements, isotropic properties, and moderate fiber volume fraction (typically less than 2% depending on fiber type and characteristics) make it especially suitable for critical elements in seismic applications where high performance such as energy absorption, steel/concrete deformation compatibility, and damage tolerance are required. The expected application of ECC are the wall members as suitable energy absorption devices for RC structures and the RC structural elements under high stresses like short span beams, base of columns or walls and connection part of elements. Decrease the damage of structures affected by earthquake is an objective. Response deflection of structures and damage of structural elements should be reduced for not only life safety but also property protection (save money for repair). Applications to both new structures and in retrofitting of existing R/C structures to withstand future earthquakes are considered. The ultimate goal of this collaborative effort is to develop design guidelines for practical structural systems containing ECC elements. Some mechanical properties of ECC material and structural performances of beam, column and wall elements have been tested and analyzed.

Tension-compression reversed cyclic test with cylindrical specimen was conducted to observe the uniaxial mechanical properties of PVA-ECC. A new testing method was developed for this test, since the basic data of material properties under cyclic loading is necessary to discuss about the application to the seismic resistant structures. From this test, PVA-ECC with 1.5 % of fiber volume fraction exhibited unique properties like strain-hardening with strain capacity of around 1.5 % and multiple cracking in tension. Cyclic loading tests of beam and column elements were conducted to investigate the upgrading effects of elements by ECC in structural performance. Test results of the PVA-ECC elements were discussed in comparison to the conventional RC elements with the same arrangement of steel bars. The result of this study indicates that the brittle failures as shear failure and bond splitting failure observed in the RC specimens can be prevented by using ECC in place of concrete. As a result, the PVA-ECC elements indicate excellent ductile manner. This means that PVA-ECC worked as lateral reinforcements to resist against not only shear and bond splitting but also concrete expansion after yielding of the elements by confinement. The maximum shear crack width up to 5% radian in deflection angle of some PVA-ECC beams were less than 0.3mm, which is a maximum limit value for durability. Through the test and FEM analysis, it was clarified that PVA-ECC has much feasibility to upgrade the structural performance and damage tolerance of building structures. For the future application, it is necessary to develop constitutive models for FEM analysis to estimate the resistant mechanism of PVA-ECC structural elements and to develop a performance evaluation method.

## U.S. SIDE PROGRAM

The topics covered in the U.S. side research projects include: (a) development of advanced fiber reinforced cementitious composites with very high ductility, such as FRC made with polyvinyl alcohol (PVA) fibers called PVA-Engineered Cementitious Composite (PVA-ECC), (b) development of innovative structural systems using conventional and advanced composite materials, and (c) selective use of high performance cementitious composite materials in critical regions of composite and hybrid structures. A brief description of the individual projects is given in the following:

**Ductile Engineered Cementitious Composite Materials and Elements for Seismic Structural Applications**

(P.I. - V. Li, University of Michigan)

The reconnaissance of structural damage caused by earthquakes reveals weaknesses in the performance of buildings and infrastructure, even if built in accordance with current code provisions. This project aims at improving the seismic resistance of civil engineering structures in seismically active regions in the U.S. and Japan. In a collaborative effort, research groups from both countries involving academic laboratories, the construction industry, and government institutions, are developing new materials, structural elements and system response concepts, which can significantly improve the safety and feasibility features of today's structures. The building block of these innovations is a new class of fiber-reinforced cement-based materials called Engineered Cementitious Composites (ECC), which are developed based on micromechanical design principles. ECC contains a moderate fiber volume fraction (<2%) and shows tensile strain-hardening behavior accompanied by the formation of multiple cracking. These unique features result in an ultra-ductile deformation response, which makes this material very suitable for seismic structural applications.

Wall panel elements made of ECC without structural reinforcement were developed and analyzed under shear load. The ductile deformation behavior of ECC material resulted in large energy absorption capacity of the panels, which can be used in seismic retrofit as energy dissipating elements. The shear resistance of ECC was further demonstrated in beam tests. Despite the absence of structural shear reinforcement, these elements maintained load-carrying capacity upto a considerable degree of deformation.

Recent investigations have focused on using ECC in combination with various reinforcement materials in members of structural frames [Li and Fischer 1999]. Fundamental research on this application involved the tension-stiffening effect of reinforced ECC elements. The load-deformation characteristics of the tension specimen were of particular interest, as well as the strain distribution in the reinforcement. It was found that the multiple cracking property of ECC matrix material resulted in a well-distributed deformation pattern along the axis of the specimen as opposed to a localized single crack opening in conventional reinforced concrete elements. Similarly, the subsequent uniform strain distribution in the post-yield range results in a better utilization of energy dissipating capacity of the steel reinforcement. The contribution of the ECC matrix to the load-carrying capacity was significant, particularly in the inelastic deformation regime of the reinforced composite. The ability of reinforced ECC elements to distribute the deformation demands along their length is the most important feature of such composites and will have impact on structural design concepts for improved ductility and seismic resistance. Existing constraints in material selection can be overcome and combinations with other advanced materials, such as FRP, can lead to high performance structures with a high degree of safety, reliability and feasibility.

**Use of ECC in Exterior RCS Joints for Confinement**

(P.I. - J. Wight, University of Michigan)

The research program on seismic behavior of exterior RCS (Reinforced Concrete Column-Steel Beam) connections at the University of Michigan included the testing of one subassembly with ECC, Engineered Cementitious Composite, in the joint region. Because of the excellent tensile properties observed in the ECC material, the joint transverse reinforcement was totally eliminated, making the joint detail simpler and reducing steel congestion in the connection. This specimen showed an excellent load vs. displacement response. The specimen was subjected to lateral displacements of up to 5.0% story drift, showing no loss of strength. Compared to the control specimen, which had regular concrete and 0.9% of transverse reinforcement volumetric ratio in the joint, this connection was 50% stronger and had a better stiffness retention capacity. It should also be mentioned that the ECC material was able to sustain shear deformations greater than 0.02 radian with no signs of deterioration, contrary to the observations made in the specimens with regular concrete. Finally, the use of ECC material in the joint region effectively controlled the slippage of longitudinal column bars, even after yielding occurred.

**FRC-Encased Steel Joist Composite Frames for Seismic Resistance**

(P.I. - S. Goel, University of Michigan)

The research work in this project is concerned with development of fiber-reinforced concrete (FRC)-encased open web steel joist composite frames for seismic resistance [Khuntia and Goel 1999]. This new and innovative system completely eleminates the need for any shear connectors between steel joists and surrounding concrete as well as that for conventional longitudinal and transverse reinforcement, all of which are quite labor intensive. All connections in the system are steel-to-steel. Therefore, the system can be used with cast-in-place or precast construction. It also allows the system for use in unbraced moment frames as well as braced frames. In addition, the design of joints can be signficantly simplified.

The main purpose of encasement of open web joists in concrete is to prevent buckling of the chord or the web members under large displacements. The use of FRC in place of normal concrete maintains the structural integrity of the section with much improved resistance to spalling of concrete cover. Besides, due to signficant post-cracking tensile strength of FRC, the system possesses excellent shear strength, thereby, allowing the structure to yield in ductile flexural mode.

In the initial phase of the study tests were carried out on half-scale beam specimens subjected to reversed cyclic loading. In the test program, the main parameter of study was the configuration of steel elements. The results were very encouraging. The two materials interact in a way so as to provide stable hysteretic behavior with excellent energy dissipation and ductility. Ten additional beam specimens were tested under monotonic loading in order to understand the basic behavior of this new composite system. The results showed that the presence of steel fibers as well as the steel joists remarkably enhances the shear capacity of the system, thus, making it very suitable for seismic as well as non-seismic loads.

In the final phase, a half-scale, one story, one-bay frame was designed by using the results obtained in the previous phase. Strong column-weak beam concept was used for proportioning the frame members. The results showed ductile and stable hysteretic behavior. The study indicates that this type of composite framing system is very effective for seismic resistance. Pinching of hysteretic loops due to reinforcing bar pull-out, as many a times occurs in conventional RC members and joints, does not arise in the proposed system due to welded connection between the steel elements. The study shows that plastic design (yield mechanism) method can be successfully applied to this structural system.

**High Performance Composite Frame System Utilizing Advanced Cementitious Composites**

(P.I. - N. Krstulovic-Opara, NC State University)

The main objective in this research project is to explore a novel approach in design and construction of seismic resistant building structures through selective use of advanced cementitious composite materials including: Slurry Infiltrated Steel Fiber-Mat Concrete (SIMCON), Slurry Infiltrated Fiber Concrete (SIFCON), and High Strength-Lightweight Aggregate Fiber Reinforced Concrete (HS-LWA FRC). The use of these materials is made to develop a novel, partially-cast-in-place High Performance Composite Frame System (HPCFS). The frame is created by first manufacturing stay-in-place formwork elements using SIMCON or SIMCON encased steel tubes. The member "core" is then cast-in-place using HS-LWA FRC. The proposed scheme should lead to: (1) faster and economical construction, (2) improved structural response, (3) reduction in element size and weight leading to reduced dead load, earthquake forces and increased usable floor space, and (4) improved durability of the structure.

The beam elements of the proposed HPFRCS consist of a central region made of stay-in-place SIMCON formwork to be filled with HS-LWA FRC, and "fuse" elements at the ends which are made of precast SIFCON. The purpose of the end fuse elements is to provide an energy "sink" by forming a plastic hinge under severe seismic loading, while the central beam region behaves elasically. Different layouts of the fuse regions have been developed and are being tested under reversed cyclic loading. The column members consist of steel tubes filled with HS-LWA FRC and encased in a SIMCON jacket. The purpose of the SIMCON jacket is to provide additional energy "sink" under extreme seismic loading, while the rest of the section remains predominantly elastic. The beam-to-column joint region is designed based on extensive research on CFT joints. Joint performance will be evaluated by testing 1/3 scale beam-column subassemblages.

**Innovative HPFRC Coupling Beam Damper Elements for Hybrid Shear Walls**

(P.I. - A. Naaman, University of Michigan)

The overall objective of this project is to study a new and innovative seismic shear wall system for use in composite steel-concrete structures. The shear wall consists of two boundary steel columns connected by coupling beam-damper elements (CBDE) which are made with High Performance Fiber-Reinforced

Cementitious Composites (HPFRCCs). The HPFRCC materials offer excellent combination of properties such as strength, toughness, energy dissipation, stiffness, ductility and damping. The coupling beam-damper elements, which act as energy dissipators and dampers under cyclic loading, are designed to dissipate energy through a shear friction mechanism. The elements are slotted and notched at mid section in order to achieve the desired behavior.

The first phase of the project was devoted to preliminary analysis and parametric study by using non-linear finite element methods. The results were used to determine the test specimen size, notched mid section, cracking model and stress concentration, etc. The FEM analyses indicated the need for confinement at the four corners of the CBDE and for using high strength prestressing strands to balance the tension and compression forces along the diagonals. Three specimens have been designed and fabricated in a special test set-up for testing under cyclic loading. The main variable in the test specimens is the type of FRC mix used: SIFCON with ZL hooked steel fibers and volume fraction of 5%, FRC spectra fibers and volume fraction of 2%, and regular FRC with hooked steel fibers at 2% volume fraction. The test specimens are designed at a scale of 1/4.5 of full size. The test results are expected to verify the findings from the analytical study.

**Innovative Composite Shear Walls**

(P.I. - A. Astaneh, UC Berkeley)

There are two main disadvantages of traditional reinforced concrete shear walls: (a) more-than-necessary stiffness, and (b) pinching of hysteretic loops. Large stiffness can result in unduly large seismic forces into the structure, and pinching of hysteretic loops results in reduced energy dissipation capacity. The main objective of this research is to develop an innovative and ductile version of traditional composite shear walls in which the above disadvantages are eliminated. The most important elements of innovation are: (a) "Rubber-shims" placed between the concrete shear wall and the boundary beams and columns, and (b) "Special Ductile Shear Studs" to connect the concrete cover walls to the steel boundary elements. The main role of the rubber shim around the boundary is to provide an elastic gap between the shear walls, which are stiff and relatively brittle, and the boundary steel elements which are relatively less stiff but more ductile. The thickness of the rubber shim gap is determined such that upto a certain drift (about 1%) the gap is not closed and the walls are not activated. The special shear studs consist of standard shear studs with a hollow cone placed at the base of the studs before the concrete is poured. The purpose of the cone is to leave certain length of the studs unembedded in concrete which makes them behave in a ductile manner when subjected to cyclic shear.

The proposed composite shear wall system is expected to exhibit two phase behavior: one during small displacement cycles, and the second during relatively larger deformation cycles representative of severe ground motions. During small cycles the concrete walls do not participate because of the gap filled with rubber shims leaving only the steel shear wall to act with support against buckling from the cover concrete wall plates. At larger displacements the concrete walls get engaged and work compositely with the core steel plate.

Detailed analytical studies along with testing work on two story wall-frame assemblies are currently in progress. Preliminary analytical studies show that the response of the proposed system is much improved over that of conventional wall-frame system. The overall goal of the study is to develop practical design and analysis procedures for the proposed system.

## CONCLUSION

Objective of Research for Innovation (RFI) is to clarify the feasibility of structural elements and systems that new materials are used effectively to obtain the various level of performance, which is higher than code requirements, to meet the social demand for building structures under the performance based engineering system. For that purpose, evaluation methods for material properties, performance of innovative composite structural elements and systems have been studied under the US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures. The research work includes Fiber Reinforced Plastics (FRP), and High Performance Concretes (HPC). Utilization of FRP materials has been studied in RC-FRP panels, repair and strengthening of existing RC members by FRP, and use of FRP in electrical facilities. Light weight concrete with specific gravity of 1.2 to 1.6 and compressive strength of 30 to 60 MPa, and advanced cementitious composites with ultra ductile behavior are under development. A few innovative composite systems consisting of steel and fiber reinforced concrete (FRC) have also been studied. In these systems, the structural elements are made of selective combinations of FRC and steel members. The combinations under study include: FRC-encased open web steel joists, and high performance FRC core encased in slurry infiltrated mat concrete (SIMCON) shells for reinforcement as well as stay-in-place form work. Studies on selective use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in critical elements and regions of composite structures, such as joints and connections of precast elements, have produced excellent results.

## REFERENCES


Khuntia, M. and Goel, S.C. (1999), "FRC-Steel Joist Joist Composite Frames for Seismic Resistance", *Earthquake Spectra*, Volume 15, Number 1, pp 87-104.

Li, V.C. and Leung, C.K.Y. (1992), "Steady-State and Multiple Cracking of Short Random Fiber Composites", *Journal of Engineering Mechanics*, Vol. 118, No. 11, ASCE, pp 2246-2264.

Li, V.C. and Fischer, G. (1999), "Interaction Between Steel Reinforcement and Engineered Cementitious Composites", *Proceedings of High Performance Fiber Reinforced Cement Composites 3 (HPFRCC 3),* Ed. H.W. Reinhardt and A. Naaman, RILEM Publications S.A.R.L., PRO 6, pp 361-370.