Indo-US Joint NEES Workshop
on
International Collaborative Research in Earthquake Engineering

January 3-5, 2005

IIT Bombay
Powai, Mumbai 400076
India

Coordinators:
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Contents

Introduction

The **Indo-US Joint NEES Workshop (IUJNW)** on **"International Collaborative Research in Earthquake Engineering"** was jointly organized and supported by IIT Bombay (IIT Bombay Thrust Area Fund) and the US National Science Foundation (Grant Nos. CMS-9201309 and CMS-0450511), on **January 3-5, 2005**, at the **IIT Bombay** campus. The workshop was primarily aimed at extending the international collaborative research in earthquake engineering under the NEES umbrella to the leading technical research centers in India.

The George E. Brown Jr. Network of Earthquake Engineering Simulation (NEES) is a shared-use research facility for the earthquake engineering community funded by the US National Science Foundation (NSF). The NEES network provides a common research platform for all the leading US research universities in order to accelerate progress in earthquake engineering research.

The workshop was a result of the willingness of US National Science Foundation to extend beyond the (US) national boundary and the eagerness of Indian earthquake engineering researchers to participate in international collaborative research projects. Invited participants from educational institutions, research centers and government organizations of United States, Taiwan and India took part in this workshop. The participants represented a wide variety of research groups from different institutions and organizations (**USA**: National Science Foundation, University of Michigan, University of Illinois, University of California Berkeley, University of California Davis, University of Minnesota, University of Buffalo and Rice University; **Taiwan**: National Center for Research in Earthquake Engineering; **India**: IIT Bombay, IIT Guwahati, IIT Kanpur, IIT Madras, Structural Engineering Research Centre and Central Power Research Institute).

In the first technical session of the workshop, participants from US and Taiwan presented on NEES facilities and on possible research topics for international collaboration. Participants from Indian research/academic institutions presented in the second technical session on available research facilities, on plans for laboratory upgrading and on the major ongoing/recent research projects in their institutes. The next technical session consisted of serial break-out sessions on different areas of research collaboration and proposal development. In these sessions, groups for prospective collaboration were identified for various research areas in the field of earthquake engineering. Research topics of common interests based on the current status of earthquake engineering research in different countries were investigated. Besides identifying prospective research topics and research groups, other issues discussed in the break-out sessions were modes of international collaborative research under the NEES umbrella, technicalities of writing joint proposals, etc. Details of the workshop program can be found on the workshop webpage: *http://www.civil.iitb.ac.in/~sghosh/nees/*

This report presents the outcome of the workshop. It includes the workshop program; abstracts of presentations; summary, resolutions and recommendations of the workshop; group summary write-ups from identified research areas; directory of the participants and other necessary information.

Program Schedule

Venue: Jal Vihar Guest House, IIT Bombay, Powai, Mumbai – 400076, India

Monday, January 03, 2005

05:00 pm – 07:00 pm	Inauguration Inaugural presentation by P. Banerji Inaugural presentation by V. Mujumdar

Tuesday, January 04, 2005

09:00 am – 11:00 am	Session 1A: Presentations by participants from US and Taiwan on NEES facilities and possible research topics for international collaboration
11:00 am – 11:15 am	Coffee break
11:15 am – 01:15 pm	Session 1B: Continuation of presentations by participants from US and Taiwan
01:15 pm – 02:30 pm	Lunch break
02:30 pm – 04:10 pm	Session 2A: Presentations by participants from India regarding current testing facilities, plans for upgrading, major research projects
04:10 pm – 04:25 pm	Coffee break
04:25 pm – 06:25 pm	Session 2B: Continuation of presentations by participants from India

Wednesday, January 05, 2005

09:00 am – 11:00 am	Session 3A: Break-out sessions to discuss networking with NEES, topics for future collaboration and proposal development
11:00 am – 11:15 am	Coffee break
01:15 am – 01:15 pm	Session 3B: Continuation of Break-out sessions
01:15 pm – 02:30 pm	Lunch break
02:30 pm – 03:15 pm	Session 3C: Continuation of break-out sessions
03:15 pm – 03:30 pm	Coffee break
03:30 pm – 05:00 pm	Session 4: Summary presentation of breakout groups; Recommendations and Resolutions
50:00 pm – 05:30 pm	Coffee break
05:30 pm	Valedictory session

Abstracts of Presentations

1. *Subhash C. Goel:* An overview of international cooperative research on seismic performance of composite and hybrid structures
2. *K.-C. Tsai:* An international collaborative experimental program of a full scale buckling restrained braced composite frame
3. *Bozidar Stojadinovic:* nees@berkeley US-India collaboration: geographically distributed hybrid simulation
4. *Cathy French:* Multi-axial subassemblage testing (MAST) facility: description of facility and collaborative research
5. *Dan Kuchma:* Use of dense archived test data for the development of computational tools
6. *S. Thevanayagam:* Structural and geotechnical earthquake research at UB-NEES
7. *Sashi Kunnath:* Advancing dynamic soil-structure interaction modeling using NEES facilities
8. *Satish Nagarajaiah:* Variable stiffness and damping systems for earthquake protection
9. *S.R. Satish Kumar:* Laboratory testing based research at IIT Madras
10. *R.S. Jangid:* Base-isolation for near-fault motions
11. *Siddhartha Ghosh:* Earthquake engineering at IIT Bombay and the upcoming multi-axial pseudo-dynamic testing facility
12. *K. Muthumani:* Vibration control of structures under seismic excitation
13. *Durgesh C. Rai:* Experimental research and proposed pseudo-dynamic test facility at the IIT Kanpur
14. *K.B. Manjunath:* Research and testing activities at CPRI in seismic qualification of power plant equipment and structures
15. *Sajal Kanti Deb:* R&D activities on earthquake engineering and proposed dynamic testing facilities at IIT Guwahati

1. *Subhash C. Goel:* An overview of international cooperative research on seismic performance of composite and hybrid structures

Innovative combinations of two or more materials can result in very efficient and high performing structural systems to resist severe forces due to events such as earthquakes. During the past two decades or so, significant gains in the knowledge base regarding the seismic behavior of composite and hybrid structural components and systems have been made. Much of this has been accomplished through international cooperative research programs. This paper presents an overview of two such major programs: The US-Japan Research Program which spanned over a period approximately seven years from 1993-2000, followed by the US-Taiwan Cooperative Research Program which started in 2001 and completed in 2003. While the US-Japan Program was significantly broader in scope and magnitude, greater emphasis was placed on component and sub-assemblage studies and testing of full scale structures could not be undertaken due to time and budget limitations. The US-Taiwan Program was designed to fill this gap, by undertaking testing of two full size three story, three bay frames at the National Center for Research in Earthquake Engineering (NCREE), Taiwan, accompanied by related sub-assemblage tests at participating research institutions in Taiwan and analytical and design implication studies in the US. The two structural systems selected for the US-Taiwan program were: RC column- steel beam (RCS) moment frames, and concrete-filled tubular columns-steel beams-buckling restrained composite braced frames (CFT-BRBF).

There is a strong feeling within the research and professional community nationally and internationally that future structural engineering practice will move towards increasing use of performance-based design, and composite and hybrid structures because of opportunities these systems provide for innovation, and improved performance, safety and economy. The results and findings from the two international cooperative programs as briefly summarized in this paper have proven to be very valuable in achieving the above goals. Additionally, the authors believe that programs such as these may also serve as models for carrying out future large scale research projects in an environment of international collaboration as is envisioned in the U.S. National Science Foundation NEES program.

2. *K.-C. Tsai:* An international collaborative experimental program of a full scale buckling restrained braced composite frame

The Taiwan National Center for Research on Earthquake Engineering (NCREE) was officially established in 1990 with the joint effort of the National Science Council (NSC) and the National Taiwan University (NTU). NCREE brings together academic resources and researchers to carry out joint projects on pre-earthquake preparedness, emergency response, and post-earthquake recovery. The NCREE has one of the world largest earthquake simulation laboratories, equipped with state-of-the-art shaking table, servo-hydraulic actuators, a large strong floor area and two-directional reaction walls, capable of accommodating large or full scale earthquake simulation tests. In this paper, the background, objectives, missions, organization, facilities and recent research activities of NCREE are described. The facilities in NCREE are convenient for launching international experimental research programs.

In this paper, an international collaborative networked pseudo-dynamic experimental program of a full scale 3-bay 3-story buckling restrained braced frame is described in details as an example. The test frame was loaded to simulate the responses under ground motions corresponding to earthquake hazards for a highly seismic location with 50%, 10%, and 2% chance of exceedance in 50 years. The frame specimen was designed by displacement-based seismic design (DSD) procedures considering a target inter-story drift limit of 0.025 radian for the 2% in 50 years hazard level. This paper summarizes the analytical studies made before and after the tests and evaluates the frame performance. CFT/BRBF performed extremely well after the application of six earthquake load effects. Very minor changes on stiffness and damping were observed as evidenced from the free vibration tests conducted after each earthquake pseudo dynamic test. The peak story drift reached 0.023 radian at the first story after applying the 2/50 design earthquake on the specimen. Tests confirmed that the DSD procedure adopted in the design of the specimen is effective in limiting the ultimate story drift. Tests also confirmed that the response of the CFT/BRB frame can be satisfactorily predicted by using either OpenSees or PISA3D.

3. *Bozidar Stojadinovic:* nees@berkeley US-India collaboration: geographically distributed hybrid simulation

The *nees@berkeley* structural simulation laboratory is a part of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). This Equipment Site specializes in simulation of structures and structural component response under earthquake loading. It features a reconfigurable reaction wall facility and a large array of different actuators enabling a wide variety of test configurations to suite different research needs. The facility features three measurement systems: a conventional, a laser-based and a digital photography based metrification system that together give researchers unprecedented detail quantifying the deformation of the specimens and ability to store, retrieve, synchronize and annotate the collected data. The internet connectivity and the teleobservation facilities provided at *nees@berkeley* match the high standards demanded of NEES laboratories.

The principal elements of the facility are the control room, the computers, and the digital real-time controller for generating the command signals and controlling the response of the specimens. These simulation control facilities can operate stand-alone or in concert with other NEES laboratories using the algorithms for geographically distributed hybrid simulation developed at *nees@berkeley*. These algorithms are an extension of the 30-some year development of the pseudo-dynamic testing method at UC Berkeley that allow for conduct of a continuous sub-structured pseudo-dynamic test with physical or numerical sub-structures distributed geographically and connected using the internet network.

In this talk I will describe the *nees@berkeley* facilities, the algorithm for geographically distributed hybrid simulation, and address the many possibilities for cooperation with Indian researchers at ITT Bombay.

4. *Cathy French:* Multi-axial subassemblage testing (MAST) facility: description of facility and collaborative research

This presentation will briefly describe one of the equipment facilities in the NSF George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Consortium and an example of collaborative research conducted in the facility through the NEES program. The Multi-Axial Subassemblage Testing (MAST) facility, at the University of Minnesota, is one of the six large-scale structural testing systems in the fifteen-facility NEES network. A unique feature of the MAST system is its sophisticated six-degree-of-freedom controller that enables seamless multi-directional testing of large-scale structural subassemblies including components of buildings and bridges. The MAST system enables evaluation of existing systems, the effect of retrofitting those systems, and the evaluation of new systems and materials to develop durable and economical structural systems capable of resisting seismic, wind and other types of loading.

An example of collaborative research being conducted in the MAST Laboratory is the testing of a series of nonrectangular (T-shaped) structural walls. This investigation is a joint study conducted by the University of Minnesota, Iowa State University and the University of Puerto Rico at Mayaguez, with participation by a practicing engineer from the State of California. The presentation will include a brief description of the project and lessons learned engaging in the collaborative process.

5. *Dan Kuchma:* Use of dense archived test data for the development of computational tools

The NEES sites employ advanced instrumentation devices that can measure in unprecedented detail the deformations, strains, and loads in test specimens. This data will be permanently archived and made available via the internet in a format that is readily usable by the broader research community. This provides an opportunity to advance the development, calibration, validation, and use of non-linear finite element analysis tools for the seismic design of our civil infrastructure.

A stated goal of the NEES program is to "*test and validate more complex and comprehensive analytical and computer numerical models*". These improved models are essential if seismic design practice is to advance as codes-of-practice cannot adequately account for the complexity of structural systems and their response to ground motions.

The ultimate goal would be the creation of mature computational tools that once material properties and geometric details are input can provide a reasonably accurate prediction of the response of a system to seismic actions and can be used to assess the impact on performance of material and geometric details. If these types of mature numerical models are to be developed, it will require much more than dense and broadly available test data. It will also require a systematic approach for generating "*benchmark test data*", the creation of measures for assessing the capabilities and limitations of analysis tools, and it will require the active participation of researchers and designers from both the United States and around the World.

This talk will present capabilities of NEES advanced instrumentation systems, challenges and opportunities for developing reliable computational tools, as well as ongoing efforts to create a process for using computational tools in design practice.

6. *S. Thevanayagam:* Structural and geotechnical earthquake research at UB-NEES

The NEES laboratory at UB was developed to conduct testing of full or large-scale structures using static or dynamic loading and earthquake simulations. This can be accomplished by a combination of loading systems including: large scale dynamic and static servo-controlled actuators that have a cumulative capacity to apply forces of up to 1800 tons, a strong floor and a large reaction wall which are integrated with two 6-DOF 50 ton capacity shake tables that can be easily relocated in a 37 meter long trench. To achieve the high loading rates required for seismic simulation, the test equipment is supported by a high-capacity, high performance hydraulic supply and distribution system (capable of supplying up to 6000 lpm), which is operated by numerous high performance digital control systems. The facility is housed in the new UB-NEES, an expansion of the existing SEESL-Lab, and is serviced by a 40-ton capacity crane.

The new UB-NEES expansion facilities use of modern testing techniques, such as Real-Time Dynamic Hybrid Testing and Fast Pseudo-Dynamic Hybrid Testing and Dynamic Force Techniques, along with conventional Static, Quasi-Static and Dynamic Force techniques. The new form of the dynamic substructures with real time computer simulation of the remainder of the structure. This provides a more complex picture of how earthquake will affect large structures, including building and bridges, without the need to physically test the entire structure.

In addition a new very large (5x2.75x6.2 meters) geotechnical laminar box is available for use either on a single shake table ,on both shake table, or on the strong floor, for geotechnical and soils-structure interactions studies.

Networked tele-experimentation capabilities using modular and expandable tele-observation teleoperation equipment tied with the testing system using discrete and global sensors (including high resolution digital video and imaging capability) make it possible for remote collaborators to use the UB-NEES facility and to remotely observe tests and lab activity. A UB-NEES collaboration room located adjacent to the laboratory is equipped with the NEES grid enabled equipment to support the NEES collaborative activities. Such as real time tele-observations, tele-operations and group interactive consultation.

The NEES laboratories at University of Buffalo is a part of Structural engineering and Earthquake simulation laboratories (SEESL) of the Department of civil, Structural & Environmental Engineering and also one of the laboratories affiliated with the Multidisciplinary Center for Earthquake Engineering Research (MCEER).

7. *Sashi Kunnath:* Advancing dynamic soil-structure interaction modeling using NEES facilities

The evaluation of earthquake response of structures that collectively addresses highly complex time-varying phenomena - from inelastic and material-dependent superstructure behavior to nonlinear multi-directional wave transmission from bedrock to the ground surface through layered media - is the subject of dynamic soil-foundation-structure interaction (SFSI) modeling. It is now common knowledge that SFSI can significantly influence the seismic response of structural systems. Because SFSI issues are not well understood, existing approaches to incorporate these effects are generally based on simplifying assumptions which can lead to gross misrepresentations of the problem.

Advances in dynamic SFSI modeling have been hindered in the past for the following primary reasons:

a) Lack of adequate testing facilities that facilitate validation and calibration of analytical models
b) Lack of communication between structural and geotechnical engineers

The availability of modern testing facilities through NEES has now largely eliminated the first concern. Ultra small scale testing on centrifuges in conjunction with on-site field testing and large-scale laboratory testing using shaking tables with soil boxes offer a range of options to validate and calibrate analytical developments.

The second issue listed above, however, is far more critical and must be addressed with a sense of urgency. This short presentation will highlight issues in structural and geotechnical modeling that are essential to advancing the state of the art in dynamic SFSI modeling. The utilization of features and facilities offered by NEES provide a unique opportunity to foster collaborative research on a scale that was not possible in the past.

8. *Satish Nagarajaiah:* Variable stiffness and damping systems for earthquake protection

Seismic response reduction can be achieved by using variable damping, and/or variable stiffness, in structures, especially during pulse type of excitations, wherein conventional damping may not provide adequate protection. Independently variable stiffness, independently variable damping, or combined variable stiffness and damping are possible alternatives available for earthquake protection. Most studies to date have considered structures with variable dampers and shown their effectiveness in reducing the seismic response. Structures equipped with both variable stiffness and variable damping systems have not been studied to date; such systems might provide the best performance. Hence, systems that can independently vary both stiffness and damping are presented.

The effect of combined variable stiffness and damping in reducing the response of single degree of freedom (SDOF) systems and multi degree of freedom (MDOF) systems subjected to pulse type of seismic excitations is presented. Nonlinear response spectra and time-histories are presented to show the reduction of response, in SDOF and MDOF systems subjected to pulse type of excitations. It is shown that the independently variable stiffness and variable damping systems can provide response reduction over a broad period range and can be implemented in practice. New fluid based variable stiffness and damping device development is presented. Introduction of such a compact fluid based variable stiffness and damping device presents new opportunities and challenges in earthquake engineering and can be studied under the NEES initiative.

9. *S.R. Satish Kumar:* Laboratory testing based research at IIT Madras

The structural engineering laboratory of IIT Madras is one of the most active laboratories of its kind in India. Established in 1972, the lab has enabled research and development work on several topics in the area of structural engineering. The present paper gives information of the facilities and equipment available and highlights the contribution of the lab in aiding the understanding of the behavior of several structural systems. The major contributions of the lab in the past are reviewed. Some of the recent tests carried out in the lab are described. These include static tests on slender RC beams and RC box girder bridges, high-cycle fatigue tests on railway sleepers and FRP box girders. low-cycle fatigue tests on RC beam-to-column joints, strengthened brick-wall panels and steel connections and non-buckling braces. In addition tests for strain ratchetting behavior and crack growth in piping components under internal pressure, meant for the nuclear industry are also described. Several other tests performed either for research or for consultancy are also reviewed. Recently, the lab has procured a suite of actuators for testing multi-degree-of-freedom systems and pseudo-dynamic tests. The paper concludes with a discussion on the future development plans and prospects of the lab.

10. *R.S. Jangid:* Base-isolation for near-fault motions

Several seismologists have suggested that base-isolated buildings can be vulnerable to the large pulse-like ground motions generated at near-fault locations. This lead to considerable interests to the researchers and recently several studies for understanding the dynamic behaviour of base-isolated buildings under near-fault motions were reported. The bearing displacements under near-fault motions ware found to be significantly large that can cause instability in the isolation system. In the present study, analytical seismic response of multi-story base-isolated building is investigated under near-fault motions. The normal component of six recorded near-fault motions is used to study the variation of top floor absolute acceleration and bearing displacement of the isolated building. The superstructure is idealized as a linear shear type flexible building. The force-deformation behaviour of the isolation system is modelled by the bi-linear characteristics. The governing equations of motion of the isolated structural system are derived and the response of the system is obtained numerically. The response of the isolated building is plotted under different system parameters such as superstructure flexibility, isolation period and bearing characteristic strength. The comparison of results indicated that for low characteristic strength there is significant displacement in the isolation system under near-fault motions. There also exists a particular value of the characteristic strength of the isolator for which the top floor acceleration attains the minimum value. Further, the optimum characteristic strength is derived for different system parameters under the near-fault motions. The criteria selected for the optimality is to minimization of both top floor acceleration and the bearing displacement. The optimum characteristic strength of the isolator is found to be in the range of about 10 percent of the total weight of the building under near-fault motions. In addition, the response of seismically isolated bridge is also investigated and found that there exists a particular value of the friction coefficient for which the pier base shear and deck acceleration attain the minimum value under near-fault motions.

11. *Siddhartha Ghosh:* Earthquake engineering at IIT Bombay and the upcoming multi-axial pseudo-dynamic testing facility

Indian Institute of Technology Bombay has been actively pursuing research and education in the field of earthquake engineering since mid-1980s. The number of faculties whose primary focus is in earthquake engineering has grown up to seven (5 in structural earthquake engineering, 1 in geotechnical earthquake engineering, and 1 in seismology), at present, and their research works cover a very diverse range of topics within the broad discipline of earthquake engineering. IIT Bombay recognizes the contribution of its earthquake engineering group and recently the Institute Strategic Planning Committee (ISPC) has selected earthquake engineering as one of the six “thrust areas” of the institute. The earthquake engineering group has come up with the proposal of establishing a multi-disciplinary Center for Advanced Research in Earthquake Engineering (CAREe) for state-of-the-art research, development and outreach policies; including organizing training programs, initiating and participating in development of public policies, and developing national standards. An important focus of the earthquake engineering thrust area group is going to be the enhancement of available research (experimental and analytical) facilities.

The major addition to the existing experimental facilities will be:

a) A hybrid multi-directional testing facility for seismic performance evaluation of large-scale structure and sub-structural systems (or sub-assemblages), and
b) A seismic observatory.

The structural (seismic) performance evaluation facility will include the following primary components: a combined system of strong floor and multi-directional strong wall, a set of dynamic actuators of different force and stroke ranges, digital control systems and high-speed data acquisition systems. The seismic observatory will be equipped with a state-of-the-art broadband digital seismograph.

The presentation will include a brief discussion on research interests of the faculty members, existing (experimental and analytical) research facilities, and future plans of enhancing these facilities.

12. *K. Muthumani:* Vibration control of structures under seismic excitation

Seismic performance of framed buildings can be greatly enhanced by adding passive energy absorbing devices and/or base isolators to modify the structural dynamic characteristics. This method has found wide applications in structural engineering because of its cost-effectiveness and high reliability and they can be readily incorporated in existing structures as a retrofit measure. Damping prevents energy build-up and reduces the system response especially near resonance conditions, where it governs the response.

Yielding type elasto-plastic metallic dampers having 'X' shape are used to increase the energy dissipation ability of structural systems subjected to earthquake loading. A methodology for designing a suitable damper scheme is developed for moment resisting frames to enhance the energy dissipation capacity. Shake table tests of sweep sine and random nature are conducted on the frame before and after adding the damper scheme. The increase in the damping and its consequent response reduction of the frame are studied. Based on this exercise, a step-by-step design procedure is presented for designing dampers of metallic type for moment resisting frame subjected to earthquake loads.

Static and dynamic tests are also carried out on other passive energy dissipating devices like lead extrusion damper, visco-elastic device and magneto-rheological dampers to evaluate the basic characteristics of the device.

Seismic base isolators are laterally flexible elements such that the horizontal frequency of the isolated structure in the first mode is typically between 0.5 Hz and 0.75 Hz. Provision of steel reinforcement is mandatory to enhance the vertical stiffness. Basic studies are carried out to evaluate the dynamic characteristics of such isolators designed by the method developed at our centre.

Shape Memory Alloys are well known for their better superelastic properties, repeated absorption of large amounts of strain energy without permanent deformations and extraordinary fatigue resistance under large cycles are suitable for vibration control purposes. Studies are conducted on Ni-Ti metal alloy wire with 55% Ni and balance titanium. Tension cyclic tests are carried out at different prestrains – each prestrain having a certain number of cycles of minimum three different amplitudes – on a single wire till failure.

13. *Durgesh C. Rai:* Experimental research and proposed pseudo-dynamic test facility at the IIT Kanpur

Faculty members in structural engineering at IIT Kanpur have been pursuing experimental research in the area of earthquake engineering largely using the facilities available for slow cyclic testing of structural elements and assemblies and vibration survey of both ambient and forced type using in-house built eccentric mass shaker. A 250 kN and 500 kN servo-hydraulic actuators were employed to study reduced scale modes of reinforced concrete (RC) moment resisting frames (MRFs) with brick masonry infills; beam-column joint sub-assemblages of RC, steel and precast RC MRFs; pre-stressed concrete bridge girders; built-up beam columns and aluminium shear links as energy dissipation device. A number of studies have been carried out in understanding the dynamic behaviour of buildings under ambient and forced vibration conditions.

In the next major expansion of the existing structural testing facility is planned to undertake the Pseudo Dynamic Testing of large structural systems. This is a logical extension of the current slow cyclic studies performed so far on sub-assemblages of reduced-scaled.

The following infrastructure is planned:

a) A new L-shaped integrated 10 m x 15 m x 3.5 m three-cell box girder of strong floor and reaction wall of 10 m height supported by 2.5 m deep buttresses on 3 m centers. The structural floor will have tie-down points (anchorages) at 1 m centers will have a capacity of 1500 kN in shear and 2000 kN in tension/compression at buttresses.
b) Fatigue rated servo-hydraulic actuators 1000 kN each; reaction wall
c) An overhead handling facility (electrically operated traveling crane of 200 kN capacity); and
d) Virtual instrumentation based 128 channel data acquisition system.

Funds have been made available from FIST scheme of DST, Lab grant of NPEEE of MHRD, other research grants and grants from the IIT Kanpur. Some equipment have already been purchased, however, civil works are still in drawing board stage. The facility is expected to complete by the end of year 2005.

14. *K.B. Manjunath:* Research and testing activities at CPRI in seismic qualification of power plant equipment and structures

Earthquake Engineering and Vibration Research Centre equipped with tri-axial seismic shaker table with six degrees of freedom has been established at Central Power Research Institute, Bangalore for carrying out applied research, testing and certification in the field of seismic engineering. Simulation tests can be carried out on prototype and scaled down models weighing up to 10 tonnes, to check the reliability of electrical equipment and critical structures of nuclear power plants, dams, bridges and high rise buildings etc. The Centre has carried out seismic qualification tests on various equipment like Switchgear, Transformer, Battery Bank, UPS, Electrical Panel, etc. The Centre has carried out design and development of Earthquake Resistant Bamboo structures. The details of seismic qualification of equipment and earthquake resistance bamboo structure are discussed in this paper.

15. *Sajal Kanti Deb:* R&D activities on earthquake engineering and proposed dynamic testing facilities at IIT Guwahati

Northeast India and the adjoining region fall in the most intense seismic zone of the world. In view of the above, research and development activities on *Earthquake Engineering* have been given top priority in the IIT Guwahati, which is the only center of excellence in technical education and research in this part of the country. In this presentation, seismicity of northeastern region of the country will be highlighted briefly. *Earthquake Engineering* component in the Civil Engineering Curriculum for undergraduate and postgraduate program will be discussed. Research works on *Earthquake Engineering* carried out by postgraduate students and research scholars will be highlighted. Ongoing sponsored research programs on Earthquake Engineering undertaken at IIT Guwahati will be presented. IIT Guwahati has an ambitious plan of creating well-equipped Structural Testing Facilities. The dynamic testing facilities, including *uniaxial earthquake simulator facilities and pseudo-dynamic testing facilities*, proposed to be created at IIT Guwahati will also be highlighted. Finally, possible collaborative research program under NEES umbrella to be carried out at IIT Guwahati will be identified.

Summary, Resolutions and Recommendations

1. Summary

The objectives of the workshop were: (1) to develop plans to link some leading research facilities in India with the global George E. Brown Jr. NEES network, and (2) to discuss opportunities and development of a long range collaborative research program within the NEES Research Program of US National Science Foundation.

The technical presentations and discussions were held on January 4-5, 2005, on the campus of IIT Bombay. The workshop was attended by eight participants from the US, one from Taiwan, and ten from India.

On the first day of technical sessions (January 4, 2005), the participants made presentations briefly describing some ongoing research programs utilizing capabilities at various NEES facilities in the US, research facility at the National Center for Research in Earthquake Engineering (NCREE) in Taiwan, and at various leading academic/research institutions in India.

On the second day (January 5, 2005), detailed discussions were held with a focus on developing and utilizing existing facilities to carry out collaborative research projects of mutual interest, identifying priority research topics, possible sources of funding in each country, and exchange of research personnel, in the short as well as long term. Following topic areas were identified at this time as priority areas of mutual interest:

1. Structural control/response modification
2. Structural health monitoring/smart structures
3. Advanced materials, composite and hybrid structures
4. Performance-based design
5. Retrofit and upgrading of existing structures
6. Bridge structural systems
7. Soil-foundation-structural interaction/Infrastructural systems

Brief summaries of discussion on the above topics are included elsewhere in this report.

The workshop concluded with a final session on the second day (in the presence of Prof. Ashok Misra, Director of IIT Bombay), with presentations of some concluding remarks and a brief summary and recommendations of the workshop, as agreed upon by all participants.

2. Resolutions

1.It was agreed that the workshop was successful and fruitful for all participants in a cordial environment hosted by IIT Bombay.

2.Recognizing the need for building sustainable “modern age” infrastructure for the coming century, and the hazard posed by earthquakes to property and human lives, the participants most enthusiastically agree that a well planned long range collaborative research program of international scope be established in the field of earthquake engineering. The program will utilize personnel, facilities and modern information technology that are available globally in order to solve the related problems and make progress as quickly as possible.

3. Recommendations

1. Planning effort should be initiated immediately in order to formulate a comprehensive (Indo-US-Taiwan) Joint Collaborative Research Program, which may be carried out under the auspices of Global NEES Research Program. This planning effort should result in a detailed recommended program to be carried out over a period of 10 years, covering multidisciplinary aspects of the problems to be solved.

2. Planning groups on each side as well as a Joint Planning Group should be formed in order to formulate the Joint Collaborative Research Program. Planning groups should meet as frequently as needed in order to complete their report within a period of one year.

3. Leading research laboratories should be encouraged to form links with Global NEES facilities.

4. In the short term, individual researchers and institutions are encouraged to propose and undertake small to moderate size collaborative research projects on topics of mutual interest.

5. Active exchange of graduate students, post-doctoral fellows and faculty, as needed to carry out the collaborative research work, should be encouraged.

6. Funding agencies at the government, industrial and institutional level are urged to provide financial support needed for the facilities, and conduct of the recommended research program.

Group Summary Reports

1. Structural Control/Response Modification

Group Members: S. Nagarajaiah (Rice University), P. Banerji & R.S. Jangid (IIT Bombay), K.B. Manjunath (CPRI Bangalore)

During the Indo-US Joint NEES workshop, Pradipta Banerjee, K. B. Manjunath, and Satish Nagarajaiah decided to explore collaborative research in structural control. Initial discussions centered on tuned liquid dampers as a possible topic. Nagarajaiah suggested possible collaboration on passive tuned liquid dampers and smart tuned liquid dampers. Proposal could be developed for submission to the US National Science Foundation (NSF) and/or to the Indian Department of Science and Technology. Nagarajaiah described efforts to conduct research that would lead to practical applications suitable for implementation in India. In response to which Vilas Mujumdar, program director, US NSF, suggested that the research should be fundamental in nature for the US NSF to fund it. Nagarajaiah responded that the proposal would have basic fundamental research as well as practical deliverables. Nagarajaiah, Banerjee, and Manjunath would develop the proposal jointly. The following white paper on passive tuned liquid dampers and smart tuned liquid dampers is proposed for initial consideration.

<u>Tuned Liquid Dampers</u>
Extensive investigations of the one-dimensional tuned liquid damper (1D-TLD) and its application as tuned mass damper for structural response control have been reported in the literature. Detailed mathematical formulations and analytical models necessary to simulate the fluid sloshing motion in a 1D-TLD have been proposed. However, TLD devices, which can function under bidirectional vibrations, have not been studied in depth to date. Bi-directional passive rectangular TLD devices with damping screens and their performance as vibration absorbers has not been studied. Such rectangular tanks are widely used in India and in the US to store water on top of medium rise or tall buildings. Rectangular tanks can have different fundamental frequencies in two directions. Experimental shake table tests of such bidirectional rectangular TLD are proposed. An experimental setup of a rectangular fluid filled tank supported by a rigid mass structure will be studied. Both square and rectangular tanks will be studied. The shake table tests will be performed at CPRI-Bangalore. The structure 2D-TLD system would be subjected to sinusoidal and random excitations. Detailed experimental observations will be used to develop and validate analytical models for 2D-TLD. Existing analytical models for 1D-TLD cannot be directly applied to the 2D-TLD. Detailed dynamic analysis of the structure-2D-TLD system will be performed. Detailed performance evaluations of the 2D-TLD for tuned mass damping effect will be performed. Detailed response performance comparisons between the 2D-TLD and 1D-TLD will be performed. Applications in medium rise and tall buildings will be investigated analytically.

Smart Tuned Liquid Damper

Semi-active or smart tuned liquid damper (S-TLD), wherein the frequency of the TLD can be tuned in real time will be evaluated; such a system will be robust to changes in building stiffness due to damage and deterioration. In comparison, the passive tuned mass damper based on TLD looses its effectiveness under such building stiffness variations. The frequency tuning of the S-TLD will be achieved using new control algorithms based on time-frequency techniques, such as instantaneous frequency and Hilbert transform, short time Fourier transform, and Empirical Mode Decomposition. Experimental setup for the S-TLD will be developed and tested on a shaking table at CPRI-Bangalore. The smart tuned liquid damper concept is a state of the art concept that has not been studied to date, and is a challenging fundamental problem that would be of interest to US-NSF.

2. Structural Health Monitoring/Smart Structures

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With India, Taiwan and the United States sharing an identical set of natural and man-made vulnerabilities, there is a clear need to foster Indo-US joint collaboration on the topic of structural health monitoring and smart structures. For example, two recent earthquakes to strike India and the United States, specifically the Bhuj Earthquake (Gujarat, India - January 2001) and the Northridge Earthquake (Los Angles - January 1994), both resulted in tremendous loss of life and property. As a result of such inevitable disasters, the structural inventory of India and the United States would greatly benefit from the adoption of mitigation (control) and prognosis (sensing) technologies. In recognition of a shared interest and the potential for synergistic collaboration, structural health monitoring and smart structures are included as a priority research area of the growing Indo-US collaboration.

There are many research needs that can be identified in the fields of structural health monitoring and smart structures. The purpose of structural health monitoring can be described in terms of pre- and post-event. Before a disaster, structural health monitoring can provide empirical data and analysis tools for 1) refining design models, 2) optimizing retrofit strategies and 3) identifying structural vulnerabilities. After a catastrophic event, structural health monitoring provides a mechanism for the prioritization of emergency response resources as well as rapid identification of unsafe structural conditions. Within the context of the Indo-US collaboration, the research needs for structural health monitoring are evenly divided into four primary thrust areas: advanced sensor transducers, data-driven monitoring systems, enhanced data processing, and control/sensor fusion.

a) Advanced sensor transducers entail the design of novel transduction mechanisms for improved measurement of the dynamic response of structures. Included in this thrust is fundamental research in the area of microelectromechanical system (MEMS) sensors, fiber optic strain gages, among other emerging micro-scale sensor technologies. An emphasis of the research conducted in this area will include further reduction of sensor transducer sizes, improved measurement accuracy and substantial cost reductions.

b) Data-driven monitoring systems refer to a new class of structural monitoring systems in which sensor hardware and embedded data interrogation are fully merged. Examples of research in this area include the design of low-cost wireless sensing units, optimization of multi-tier network topologies, and sensor-centric embedded data interrogation algorithms.

c) With monitoring technologies like wireless structural monitoring systems growing in research and industrial popularity, unique research problems are emerging. In particular, wireless sensors are provided with impressive computational autonomy; therefore, optimal utilization of this decentralized computing network must be further explored. Key research challenges associated with this thrust include low-power usage strategies and decentralized computing algorithms for collaborative problem solving by a wireless sensor network.

d) To deliver on the promise of smart structures, ultimately the advances in active, semi-active and passive structural control must be fused with recent advances in smart sensors. Research opportunities in this research thrust include the design of comprehensive structural control and monitoring systems. Damage detection and decentralized computing will also play major roles in a next-generation of structural control systems.

3. Advanced Materials, Composite and Hybrid Structures

Group Members: S.C. Goel (University of Michigan), K.-C. Tsai (NCREE), D.C. Rai (IIT Kanpur), B. Stojadinovic (University of California Berkeley)

There is a strong feeling among the research and professional community internationally that future structural engineering practice will move towards an increasing use of performance-based design, using new materials, composite and hybrid structures because of opportunities these systems provide for innovation, and improved performance, safety and economy. Research work carried out during the last ten years or so under international cooperative programs, such as the US-Japan Cooperative Research Program on Composite and Hybrid Structures followed by testing of full-scale frames under US-Taiwan Cooperative Research Program, have produced a wealth of information, some of which has also found its way into current design practice. Nevertheless, continuing development of new and advanced materials, such as special property steels, and high performance cementitious as well as plastic composite materials, provides constantly increasing opportunities for developing innovative structural elements and systems. Continued research effort is needed in the area of innovative new materials, and structural elements and systems for use in new construction as well as for repair and upgrading of existing infrastructural systems, such as buildings, bridges, and highway and other transportation systems.

Development of new structural systems and use of new materials should be conducted in parallel with the development of performance-based design procedures for such systems. Guidelines for computer modeling of new structural elements (for demand evaluation) and data on strength and deformation capacity of new structural elements and structures (for capacity evaluation) is essential for implementing probability-based design procedures. Cooperation in this area, involving experimental evaluation of the new structural systems in several laboratories simultaneously, is very likely to bring about speedy development and adoption of such new structural systems.

Rai, Goel, Stojadinovic and Tsai are already in the process of planning and initiating collaborative research work in this area on further development of the light truss reinforced fiber concrete structural system. This structural system has many advantages, two very important: 1) it behaves at least as well as conventional reinforced concrete framing systems, while affording prefabrication and significantly simpler joint design; and 2) it can be implemented in the US, India and Taiwan using existing building technology and some training: no expensive materials or proprietary technologies are used.

4. Performance-Based Design

Group Members: S.C. Goel (University of Michigan), S. Ghosh (IIT Bombay), B. Stojadinovic (University of California Berkeley), D. Kuchma (University of Illinois Urbana Champaign), K,-C. Tsai (NCREE)

New seismic design codes are moving towards adopting a performance-based design (PBD) framework. The goal of performance-based design is to produce structures that have predictable performance under multiple levels of earthquake hazard. In order to do so it is essential that the behavior of structures be targeted in advance, both in the elastic as well as inelastic ranges of deformation. Consequently, design issues such as, determination of design lateral forces or deformations consistent with selected hazard level(s), determination of member and sub-structure likely capacities, determination of member strength hierarchy, selection of desirable energy dissipation mechanism, and confirmation of actual strength and drift capacity of the designed structure etc., become the primary elements of a performance-based design procedure.

Research work is needed to develop practical new design methodologies and approaches that will fit into a PBD framework in order to produce structures with targeted and controlled response under multiple levels of earthquake hazard, including consideration of total life cycle cost. Deterministic as well as probabilistic approaches will need to be pursued.

Goel and his associates at the University of Michigan have been working on one such methodology which is based on energy and plastic design concepts. The design approach uses pre-selected target drifts and yield mechanisms as performance limit states. The yield mechanism can be selected so as to limit inelastic activity among certain structural components or elements, or to minimize post-earthquake repair costs. Acceptable damage or available ductility could determine the target drift values. The expression for design base shear is derived by using the energy balance equation where the energy needed to push the structure up to the target drift is calculated as a fraction of elastic input energy which is obtained from the elastic design velocity spectra. The design methodology has been successfully applied to steel moment frames, buckling restrained braced frames, eccentric braced frames, and Special Truss Moment Frames. Work is currently in progress to extend the approach to composite and hybrid structures, and systems with deteriorating type of hysteretic response, including buckling type braced frames. Ghosh and Goel have already talked about teaming up to incorporate probabilistic concepts in this methodology.

Stojadinovic has been involved in the development of the PEER Center methodology for performance-based evaluation and design of structures and its implementation to bridge structures. This methodology is based on a framing total probability equation that integrates the components of seismic hazard, earthquake ground motion intensity, engineering measures of structural demand and damage and socio-economical decision variables. This integral approach provides for comparison of life-cycle costs of different designs or abilities of different structures to function after an expected earthquake. Stojadinovic and his associates have demonstrated this aspect of the PEER methodology for highway overpass bridges. Merging the design methodology developed by Goel with the PEER approach may result in a viable probabilistic performance-based method.

For evaluation and validation purposes, new performance-based methodologies such as mentioned above should be used for designing test specimens and structures in future studies.

5. Retrofit and Upgrading of Existing Structures

Group Members: D.C. Rai (IIT Kanpur), C. French (University of Minnesotta), S. Kunnath (University of California Davis), A Meher Prasad & S.R. Satish Kumar (IIT Madras)

While in the developed world, the aging civil infrastructure needs upgrading and maintenance for unabated operation; in the developing world a large number of deficient civil engineering structures needs to be retrofitted to mitigate the risk of their failure in extreme events, such as earthquakes. Experiences from the past earthquakes clearly demonstrate that existing pre-standard or sub-standard structures pose much greater risk to occupants than possibly safer new constructions. Therefore, concentrating efforts on improving the seismic response of existing structures pays much greater dividends in ensuring overall safer built environment. In order to counteract detrimental effects of continuous decay and to satisfy ever increasing design requirements, structural retrofitting and upgrading is receiving considerable attention toady than in the past by professionals and researchers alike.

Despite the obvious need, currently available analytical tools and implementation strategies have not been proved to be as effective as needed at various stages of retrofitting process, starting from the seismic evaluation phase for an accurate description of deficiencies to the final choice of an effective and economical strategy and its field implementation. The workshop participants agreed that the research efforts should be focused on those retrofit strategies, which will have wider applications, such as the one described below.

Presence of open first story has been a single major cause of damage and destruction of reinforced concrete multi-storied buildings all around the world. Although many retrofit options have been suggested to remedy the open first story problem, an effective, economical and easy-to-use method is yet to be found. Innovative use of composite and hybrid elements using steel and reinforced concrete materials offers a solution that holds significant promise based on past experience. One such retrofit strategy envisages strengthening of weaker existing RC columns with steel batten plates, providing a new moment frame of enhanced strength, stiffness and energy dissipation capacity with beams made with steel truss encased in fiber reinforced concrete. Strategic use of steel elements on existing RC columns and inside the hybrid beam provide steel-to-steel connections at beam-column interface. Considerable research experience from the past studies at the University of Michigan and planned research in this program on composite and hybrid structures will be helpful for this research effort. Some preliminary studies are already underway at IIT Kanpur.

It is expected that more innovative solutions for retrofit and upgrading of existing structures will emerge as a result of other research projects also which may be undertaken within this cooperative research program.

6. Bridge Structural Systems

Group Members: S. Kunnath (University of California Davis), P. Banerji (IIT Bombay), I. Buckle (University of Nevada), K.-C. Tsai (NCREE)

There is a wide range of issues that need to be addressed in the overall area of bridge structural systems. However, the research needs identified in this summary are limited to seismic design and evaluation of regular bridges. Long span bridges need to be addressed as a separate topic.

a) The accurate assessment of bridge behavior under seismic loading requires consideration of soil-foundation-structure interaction effects. In particular, the issue of how and where the seismic input is introduced is a daunting challenge that has not been addressed adequately. Most available ground motions are recorded at the free-field. These motions must be deconvolved to the base of the foundation. Data from down-hole arrays can be utilized to validate or calibrate analytical models used in the deconvolution process.
b) Bridge systems consist of expansion joints and abutments in addition to primary structural and foundation elements. Modeling the behavior of the elements that comprise the expansion joint (restrainers, shear-keys, etc.) and the super-structure abutment interface (bearing surface) is critical to predicting the overall behavior of the system. This includes consideration of possible impact between super-structure elements upon closure of the expansion joint gap.

c) Structure-abutment interaction is an equally important issue, particularly for bridges with integral abutments.
d) While spatial variability has been addressed in the context of long-span bridges, the potential detrimental effects of spatial variability in multi-span bridges and viaducts needs to be investigated.
e) An equally important issue that ties in with other research areas is the retrofit and rehabilitation of bridges for seismic loads. The use of energy dissipating devices, isolation systems and new materials (high performance composite materials) that have found application in building systems can be extended to bridge structures.
f) The availability of modern testing facilities through NEES has now facilitated a range of options to validate and calibrate analytical developments: from ultra small scale testing on centrifuges in conjunction with on-site field testing and large-scale laboratory testing using shaking tables with soil boxes. The utilization of features and facilities offered by NEES provide a unique opportunity to foster collaborative research on a scale that was not possible in the past.

7. Soil-Foundation-Structure Systems

Group Members: S. Thevanayagam (University of Buffalo), S. Kunnath (University of California Davis)

Historical earthquakes have repeatedly illustrated the significant influence of soil behavior affecting performance of constructed facilities and lifelines during earthquakes. Greater damages have occurred to structures founded on weak soil deposits prone to soil amplification, liquefaction, land slides and slope failures, or other instabilities and large ground deformations. Development and application of advanced soil characterization techniques, ground improvement techniques, foundation retrofit techniques, and foundation design methodologies can mitigate earthquake induced damage to the built environment. Although advances have been made in the past two decades to improve the understanding the behavior and characterization of soils, develop advanced ground improvement technologies, and predict soil-foundation-structure interaction behavior, observations of recent earthquake performance of bridges and buildings indicate that there exists an urgent need for improved predictive tools for foundation performances, more powerful site characterization techniques, and more quantitative guidelines for soil improvement measures, and foundation retrofit techniques.

Based on discussions between the participants of the workshop, although there are a number of specific problems that are of common interest to the two sides, the following problems have been identified as high priority topics for joint research between India and the US.

<u>Liquefaction-Induced Response of Pile Foundations</u>
Liquefaction-induced lateral spreading of sloping ground and near waterfronts continues to be a major cause of earthquake damage to deep foundations supporting bridges, buildings, harbor facilities, and other structures. Permanent lateral ground deformations induce cracking and rupture of piles at

both shallow and deep elevations, rupture of pile connections, and permanent lateral and vertical movements and rotations of pile heads with corresponding effects on the superstructure. In the US, India, Japan, Mexico, Costa Rica, Taiwan, Turkey and other countries, buildings, bridges, port facilities and other structures supported by deep foundations have been damaged in many earthquakes including several in the 1990's, with billions of dollars in damage. There is substantial gap in current engineering knowledge and understanding of the response of piles and pile groups subjected to lateral spreading, and in the procedures to evaluate bending response of pile foundations. Centrifuge and full-scale shaking table tests suggest a complicated response of the liquefied sand in the neighborhood of individual piles and pile groups, and is not fully understood.

<u>Soil-Foundation-Structure-Interaction of Bridges and Buildings</u>
Significant research has been conducted over the past three decades on improving the seismic performance of bridges and buildings. Current design specifications are now performance-based, driven by the public demand for transportation systems and other critical buildings that continue to function at some level after any earthquake regardless of any size. A decade ago, saving lives by preventing span collapse was the only goal of seismic design. Today, this is not sufficient. Minimizing repair time and interruption to traffic flow while keeping costs contained, is now a key objective, in addition to the no-span collapse requirement. This is especially true for important and critical bridges, and some owners believe it should also be true for all new bridges. Similar expectations prevail for critical facilities such as hospitals. The elevation of these standards for little or no extra cost has, in turn, increased the demand for advanced knowledge about the seismic performance of bridges and buildings, and is now setting the research agenda. Advanced research programs are being proposed by structural engineering researchers to address these concerns and develop advanced earthquake protective systems, and design methodologies. But rigorous performance-based design (PBD) also requires an understanding of the soil-foundation-substructure-superstructure systems found in all bridges and buildings. Understanding of soil-foundation-structure interaction and predictive numerical modeling tools are lacking the sophistication necessary to satisfy the requirements of PBD.

It is believed that the study of these problems and development and calibration of advanced predictive numerical modeling tools requires an experimental effort at a scale that can only now be considered, now that the NEES facilities are coming on line, along with other large-scale laboratories in India, Japan, Taiwan, the U.S. and elsewhere.

A $400,000/year project for 4 years on liquefaction[1] and a $500,000/year project for 5 years on soil-foundation-structure interaction[2] should be on the high priority list of joint research proposals taken up using research facilities in, NEES equipment sites, NEES field sites, IIT Madras/SERC Chennai, NIED Japan and NCREE Taiwan.

1: Determine the magnitude and effect of liquefaction-induced forces and displacements on piled foundations at full-, or near full-, scale using a large laminar soil box. Study scale effects by conducting parallel experiments using one or more centrifuges. Understand the mechanism and physics of lateral spreads, and scale effects. Develop correct scaling laws. Once calibrated, a range of foundation configurations could be studied using multiple centrifuge experiments.

2: Determine the influence of bi-axial, soil-structure interaction on bridge response using one, or more, large laminar soil boxes on a very large shake table (or set of tables), at full- or near-full scale. Superstructure inertia effects could be modeled either by a full-scale bridge superstructure spanning two or more boxes, or by using hybrid testing techniques and actuators applied to the column cap to simulate superstructure inertia loads. Use one or more centrifuges for component validation work. Both piled-foundation and abutment back-wall interaction studies should be undertaken. This work should also be supplemented by soil-pile interaction studies on single piles and pile groups in both stiff and soft soils using a full-scale soil pit and biaxial actuators at the pile cap.

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