An Undergraduate Research Experience in New Developments for Aseismic Building Design

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Abstract

This paper describes a two-month research experience for undergraduate engineering students specifically designed to conduct three “pilot” projects investigating new strategies to mitigate earthquake damage. The project was part of a Research for Undergraduates (REU) Site grant sponsored by the National Science Foundation, and administered in the Department of Civil and Environmental Engineering at the University of Cincinnati during the summer of 2003. This opportunity helps in attracting and retaining the brightest undergraduate students by providing special programs that capture their interests and challenge their scholastic potential. Nine undergraduate students from six different institutions participated, and included three women and six men students. The students’ scholastic standing ranged from sophomore to senior level. Each group was supervised by a Faculty Mentor, one Graduate Student Mentor, and a Lab Technician during the complete duration of the REU Site. The paper presents how the whole research program was planned and conducted, the details of the projects selected for the students, and procedures used to evaluate the impact of the project. This paper will help others in planning similar experiences for engineering undergraduate students.

1. Introduction

This paper describes the experiences provided in a Site for undergraduate research in "Structural Engineering" in the Department of Civil and Environmental Engineering at the University of Cincinnati (UC), Cincinnati, Ohio. This Research Experiences for Undergraduates (REU) Site was funded by the National Science Foundation (NSF). The purpose of this REU Site was to encourage talented undergraduates to enroll in graduate school by exposing them to research, and to increase their interest in graduate research. In this paper, first the basic approach adopted to plan the REU Site and associated activities are presented in this section, followed by a detailed description of the projects selected and executed. In the end, evaluation procedures used, and the outcomes from the whole experience are summarized. Hopefully, this documentation will help others in planning similar experiences for engineering undergraduate students.
The REU Site was successfully administered from June 23 through August 15, 2003. The total REU participants included three women (one African, one Asian and one white American) and six male (one Asian, and five white American) students. Three were sophomores, five were juniors, and one senior; and six were pursuing an undergraduate degree in Civil Engineering, one in Electrical Engineering, one in Chemical Engineering, and one in Physics and Pre-Engineering. Eight of the students came from Ph.D. granting institutions, and one came from an institution with a Masters degree as the terminal degree. The nine students were divided into three groups with three students in each, and each group worked on a separate project under the supervision of Faculty Mentors and a Graduate Student Mentor. The three projects selected for the Site dealt with understanding the behavior of building frame structures subjected to earth quake loadings, and strategies to enhance their performance.

The selection of the students was based on GPA, two recommendation letters, and an essay on why they would like to participate in this REU Site and how it relates to their career goals. In total 27 applications were received for the nine positions. All applicants had excellent scholastic qualifications, and satisfied the requirements for selection if resources permitted their support. An effort was made to recruit at least three under-represented and/or minority students. The participants were paired such that a more experienced student interacted with a lesser-experienced student, as far as their scholastic standing was concerned. All students had indicated that they have decided to pursue graduate studies after completing their B.S. degree program. Each student was given a monthly stipend of $1,000/month for 2 months, board and lodging costs, and travel expenditures.

The basic approach used was discovery through actual construction, experimental testing, observing and recording, synthesizing the data collected, and generalizations. This approach provided an opportunity for individual growth and challenge to the young and inquisitive mind. Reading material was mailed to the students four weeks prior to their arrival. This included a brief description of the project assigned, test equipment and testing procedures to be used, copies of selected reference papers, the Site administration, and expected deliverables. Each participant was also informed of the name, phone, e-mail address of their group partners, and were encouraged to contact each other.

The Project Director (author), and the three Graduate Student Mentors appointed on the project had a short meeting with the three groups every alternative day. One member of each group was appointed as the group leader for a week, and this appointment was rotated. During the daily meeting the group leaders presented orally the progress of the work, the plan for the present and next day, and asked questions. The group leaders also kept a daily log, which was reviewed by their assigned Graduate Student Mentor at this meeting and signed.

Four seminars were organized to provide training to the students: 1) use of photography to capture the visual images of test set-ups and equipment; 2) lab safety and use of modern data acquisition systems and related computer software; 3) statistical analysis techniques and software packages available for student use; and 4) principles of earthquake engineering and design. The students went to two field trips, which were to a building and a bridge construction project. Not only did these field trips enhance the students' background knowledge, but they provided an opportunity for them to interact with other professionals.
Students submitted bi-weekly technical progress reports and made presentations, which in the end were condensed to a Technical Report, a Power Point presentation, and a Poster. On the last day, each team gave a one-hour presentation, which along with the technical report and poster was judged by an invited panel of professional civil engineers, and a faculty member from the Fine Arts who had the expertise to judge visual aspects of the presentation.

Thus, the REU Site provided the students with experience in using state-of-the-art testing and data recording equipment, and a "total" experience of: learning, research, report writing, and presentation. The work accomplished by the participants in the three projects is described next in this paper.

2. Selection of the Research Projects

The principal concern of current seismic design practice is to prevent the collapse of the structure and avoid the associated loss of human life. It is, however, extremely uneconomical to design structures to remain completely elastic under strong seismic loading. Classical methods of earthquake resistant design reflect a compromise between the needs for absolute safety and economy, and are based on the concept of controlled damage under extreme seismic motions. This controlled damage may be achieved by allowing parts of the structure to yield (undergo permanent deformation). One of the projects selected for the REU Site was designed to investigate the control of such damage in coupled shear wall systems used in buildings. In building systems individual wall piers (shear walls) are coupled together to resist large lateral loads caused by earthquakes and wind. By connecting the walls to each other by means of coupling beams changes the load transfer characteristics in the walls to an axial tension-compression couple. The coupling beams are significantly strong and stiff, are designed to yield before the wall piers, and typically for the yield to occur at the junction with the wall. To decrease the probability of the coupling beam failing, in this REU project the concept of using a “fuse” at the center of the beam was explored. The fuse was made of lower yield more ductile steel. By adding a “fuse” into the coupling beam the dissipated energy will be transferred to the fuse and allow the “fuse” to bear the full shear force rather than the coupling beam. Allowing the fuse to bear the shear force when the maximum force is applied, the fuse will fail rather than the coupling beam thereby decreasing rehabilitation costs. The project was designed to explore if the fuse functions as a viable alternative to conventional means of coupled wall systems, and, if use of neoprene elastomeric pads enhances their energy dissipation characteristics. For the REU Site only two tests were planned based on the results of which a comprehensive research project was proposed to be planned for external funding.

On January 17, 1994, the 6.7 magnitude Northridge earthquake shook the greater Los Angeles area. The disaster caused fifty-seven deaths and over 1,500 injuries, as well as widespread damage to public buildings and civil infrastructure. Exactly one year later, a 6.9 magnitude earthquake shook the heart of Kobe, Japan. The catastrophe caused well over five thousand deaths and over thirty thousand injuries, as well as damage to over 180,000 buildings in and around the city. Engineers gave particular interest to Welded Steel Moment Resisting Frames (WSMF), a structural design type previously noted for its economy, versatility, and plastic deformation recovery capability. Until 1994, WSMF buildings were thought to be
extremely effective in avoiding damage caused by the cyclic, dynamic loading of an earthquake. Observations following the Northridge and Kobe earthquakes, however, found a different truth. The failure of WSMF structures led the Federal Emergency Management Agency (FEMA) to sponsor a widespread initiative known as the FEMA/SAC Steel Program. The SAC Joint Venture is comprised of three separate agencies: The Structural Engineers Association of California (SEOAC), The Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREE). The collaborative effort has three main goals:

1. The identification, inspection, and rehabilitation of existing, at-risk buildings.
2. The identification, inspection, and repair of upgrading damaged buildings following an earthquake.
3. The design and construction of new buildings to withstand such loading.

The third goal is the most important for the scope of two remaining research projects selected for the REU Site since the use of T-stubs in beam-to-column connections as a viable candidate in lieu of WSMF frames is a relatively new concept in structural design. The T-stub connection, which is a fully bolted partially restrained connection (PRC), is commonly used for multi-story frame structures because it provides the similar amount of moment carrying capacity as some WSMF connections. However, PRCs have their own shortcomings including low initial rotational stiffness and pinched hysteresis behavior due to prying action. These two shortcomings of PRCs have precluded their widespread acceptance. Two projects were selected for this REU Site, one to understand more about the moment-rotation behavior of T-stub connections and how to mathematically idealize this behavior, and the second to investigate a new strategy to decrease the prying action in T-stub connections which may reduce the pinching of the moment-rotation hysteresis loops, thereby enhancing their energy dissipating characteristics. Both the projects were planned to be continued after the REU Site, and as such the work accomplished by the REU participants was intended to be a precursor for a more exhaustive research study to be undertaken later.

The titles of the three projects selected were:

1. Project # 1: “Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections,”
2. Project # 2: “Novel Steel Frame Connection With Damping Capability,” and
3. Project # 3: “Energy Dissipating in Steel Coupling Beams Involving Splice Joint Coupled with Elastomers.”

2. Execution of the Research Projects

2.1 Project # 1: “Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections”

The primary objective of this research project was to develop analytical models that predict the response of T-stub connections under seismic loading conditions, and which could be used to perform finite element analysis of steel frames with T-sub joints connecting beams to column members. The behavior of a steel frame connection is characterized by its moment-rotation curve. The primary task assigned to the group was to use experimental test results to develop a
family of mathematical models that describe the moment rotation behavior of T-stub connections with varying degrees of sophistication. The scope of this project included both the monotonic and cyclic behavior. Monotonic behavior describes the behavior of the connection when subjected to gradually increasing static loads. This behavior is usually represented by a nonlinear curve. On the other hand, the cyclic loading describes the repetitive application of a force in a specific direction followed by an equal and opposite force, which results in hysteresis loops representing the moment-rotation behavior.

To start the REU research project, during the first week the group conducted a through literature search, discussed these with the faculty and graduate mentors, and made themselves familiar with the facilities and resources available within the Department of Civil and Environmental Engineering and the College of Engineering for fabrication of test specimens and calibration of the different instruments to be used. This included laboratories on the main campus of the University of Cincinnati, as well as the Large-Scale Structural Test Facility located at Center Hill, about two miles from the main campus. The remaining weeks of the research project dealt with analysis of moment-rotation results from previous experimental testing\(^1,2\), as well as designing, fabricating and erecting the test set-up for full-scale testing of T-stub connections subjected to cyclic loading. Though specimens for four tests were designed and fabricated, but due to time limitation only one test was conducted at the Large-Scale Structural Test Facility as part of the REU Site. Both the Project # 1 and # 2 groups worked together in erecting and conducting the test.

The test set-up used consisted of two major components: (1) a horizontal actuator, the base of which was rigidly bolted to a reaction wall and the other end of which was connected to the free end of a vertically cantilevered beam specimen to apply a cyclic (moving left and right, in one plane) load, and (2) a column specimen rigidly bolted down, perpendicular to the beam specimen, to the reaction floor of the laboratory. The beam and column specimens were connected using two T-stub specimens, two web angles, and A490 bolts. Each bolt was tightened to the exact pretension load level using “squiter” direct tension indicators (DTIs). The beams were braced at two locations along its height to prevent any out-of-plane movement. The instrumentation used included the following: 1) six Linear Variable Displacement Transducers (LVDTs), a pair mounted on each side of the beam flange to measure the separation of the T-stub at that end; 2) five strain gauged bolts used to connect one T-stub to the column flange; 2) one wire potentiometer attached to the actuator to measure its stroke movement; and 4) a load cell transducer mounted on the actuator to measure the load applied. All the electronic measuring devices were connected to a unique channel of a data acquisition system, and the application of the cyclic loading history, data collection, processing and display in real time was automated. The connection rotation was obtained by dividing the difference between the separation readings recorded by the LVDTs attached to the two T-stubs divided by the horizontal distance that separated them. The moment applied to the connection at any instant was computed by multiplying the actuator load by the beam span. The connection was tested following the SAC loading pattern until the connection failed. The moment-rotation hysteresis plots and the bolt-force variation plots were recorded by the data acquisition system. The connection tested failed by fracture of the T-stem across a bolt line. In this phase of the research, the participants learned: to install bolt strain gages; the function and operation of the different electronic data measurement equipment used; procedure to calibrate and install these equipment in the test set-
up; and the use of the computer software and data acquisition. The erection of the test itself took about two days, and one day was spent to check if all transducers functioned correctly with the data acquisition system and the calibration factors were input correctly for each. The test itself took about six hours to complete.

To construct the mathematical models, data obtained from the aforementioned one T-stub test and those available from six T-Stub connection tests performed by Swanson and Leon and Swanson was used. To first investigate the monotonic behavior of the connection, maximum moment (peak) values were found for each cycle, along with the corresponding rotation, in the positive quadrant of the experimentally recorded moment-rotation plots. A plot of these values provided an experimental “enveloping” curve in the first, positively loaded quadrant, which was considered to represent the monotonic behavior of the connection. Three functions were used to analytically idealize this “enveloping” curve, the Power Series, Exponential, and the Ramberg-Osgood Functions. Both the Power Series and the Exponential Functions modeled the experimental “enveloping” moment-rotation curve equally well for all the seven tests, and are recommended for idealizing the monotonic behavior of the T-stub connection. However, the Power Series Function has an advantage over the Exponential Function, since the tangent to the curve is uniquely defined at all points, including the origin. For the Exponential Function the tangent at the origin is undefined, and so has to be evaluated at a very small distance away form the origin.

To mathematically idealize the experimentally recorded moment-rotation hysteresis plots of the connection, three analytical cyclic models were developed which varied in mathematical complexity. These included the elasto-plastic model, the bilinear model, which uses the transition moment, and the modified bilinear model, which uses the Ramberg-Osgood characteristic yield moment and characteristic yield rotation. The Bauchinger effect was considered to model the reverse load cycle in all the models. The area under the model moment-rotation curve represents the energy dissipating capability of the connection. The elasto-plastic model is the most simplest to implement, but overestimates the energy dissipating capability of the connection, whereas the modified bilinear model is more complex and models the energy dissipation more accurately, but still over estimating it. For all the seven tests the values of the model parameters (dependent variables), were regressed to develop their prediction equations in terms of the T-stub geometric (e.g., bolt diameter, bolt pitch, bolt gage, thickness and length of T-stem, thickness and length of T-flange, etc.) and force related independent variables. In developing some of these prediction equations, in addition to the connection variables the T-stub material yield strength, obtained from the tensile strength test conducted on a coupon cut from the T-stub, was also considered as an independent variable. All prediction equations developed had an $R^2$ value much greater than 0.90 (a value of $R^2=1$ indicates a perfect fit). Error bands of the equations were defined using scatter plots, which compared the experimental and predicted values. Furthermore, sensitivity analyses were conducted for each prediction equation to verify if the impact of variation of each variable predicted similar trends as those observed for the seven tests conducted. Finally, to relatively compare the predicting capability of the three cyclic models the area under the model enveloping curve was compared to the area under the outermost loop of the experimental moment-rotation plot recorded. In this phase of the research, the students learnt the theory of regression analysis, and the use of the Microsoft Excel spreadsheet software to conduct the regression analyses and obtain the required prediction equations. The
students conducted the regression analyses, model development and validation first using the results for the six tests conducted by Swanson and Leon\textsuperscript{1} and Swanson\textsuperscript{2}, which were made available to them at the start of the second week. This enabled them to add the data for the T-stub tested in the REU Site soon after the test was completed, and to obtain revised results for the prediction equations soon thereafter. So, they spread this work throughout the project, starting from the second week.

A great benefit of this REU project was the ability to enhance the laboratory skills of the REU participants, and to train them to gain experience with instruments used during experimental testing. Calibration of prepared strain gauged bolts and tension testing of steel coupons showed to them the importance of properly prepared specimens and understanding how material characteristics affect behavior.

Photographs showing the test set-up and instruments used by the students on the project are shown in Figures 1 to 3.

2.2 Project # 2: Novel Steel Frame Connection With Damping Capability

This project was planned to be the first phase of a research project, which would be continued after the REU Site. The main objective of this project was to investigate a promising strategy to reduce the pinching in the moment rotation hysteresis, obtained when a partially restrained connection is subjected to a cyclic loading, thereby, increasing the energy dissipation capacity of the connection. The connection studied was a fully bolted T-stub connection. To increase the ductility in the connection and to keep bolt forces from increasing to a level resulting in excessive plastic deformations or bolt rupture, two rubber pads were proposed to be used. One pad was placed between the T-stub flange and the column flange. This rubber pad is of the same dimensions as the T-stub flange, and is subjected to tension and compression as the connection is loaded. Similarly, a second rubber pad was placed between the T-stub stem and the beam flange. This rubber pad is of the same dimensions as the T-stub stem, and is subjected to shear as the connection is loaded. The behavior for each type of connection was studied by testing two similar connection geometries, one without rubber pads and the other with rubber pads. In total four connection tests were proposed to be performed: two for rigid T-stub connection (without rubber pads), and two for relatively flexible T stub connection (with rubber pads). The former two tests are similar to those proposed for the REU Project # 1, and both groups jointly worked on it. Due to the time it took to get the test set-up components fabricated and erected, and the electronic transducers calibrated, only one T-stub connection test could be performed during the two-month duration of the REU Site. But, test specimens were fabricated and material test performed for all the remaining tests.

In order to fully understand the deformation capability and yielding characteristics of T-stub connections, it was essential to evaluate the load-deformation characteristics of the material used for each component of the connection. The evaluation was done by performing tensile tests on steel coupons cut out from the T-stub steel material and bolts, as well as executing shear tests on neoprene rubber pads. This group was responsible for conducting most of the material tests. They not only performed these tests for the materials used for the one T-stub tested, but also for the future connection tests to be performed.
This group also developed a computer program to evaluate the area under the enveloping moment-rotation hysteresis loop obtained from the experimental results. This area is a measure of the energy dissipating capability of the connection when subjected to cyclic loads. In this procedure, first the ultimate maximum and minimum rotation values obtained from the moment versus rotation graph were found, and data points were collected around the enveloping loop, including all peak points, as well as points in between to obtain accurate linear interpolation values. Second, all points were then translated to the first quadrant so that the whole loop falls in the first positive quadrant for ease of calculations of the areas (then there was no need to consider the sign of the moment and rotation values). The area was then divided into equal width narrow strips, and the end heights of each strip were calculated by linearly interpolating the values on either side of the strip. The area of each strip was calculated using the formula for the area of a trapezoid. Finally, the total area under the enveloping moment rotation loop was found by taking the summation of the areas calculated for all the strips selected. The computer program was configured to keep on subdividing the area into more strips, until the area computed did not vary by more than 10% from the one computed with lesser number of strips. The area under the enveloping curve is a measure of the energy dissipating capability of the T-stub connection. This methodology was applied to the six tests performed by Swanson and Leon\textsuperscript{1} and Swanson\textsuperscript{2}, and the one test performed in this REU Site. Based on the values obtained, the group rank ordered these tests according to the energy dissipating capability of the connections. The group proposed to use this software to compare the areas under the enveloping curve for a similar connection tested with and without rubber pads in the future.

Before any of the preceding tests were conducted using the heavy machinery, it was essential for this group to receive accurate training in order to appropriately test, record, and collect all data needed to proceed with the proposed testing. For example, to properly strain gauge the bolts, a lathe machine was used to drill holes of the appropriate diameter which were perfectly axially oriented and were of specified length in the unthreaded portion of the bolt shank. Because of the high risk of being injured during the drilling process rigorous training was received by this group, which included: lab safety protocol, knowledge of restricted “danger” zones within close drilling proximity, and proper drilling techniques that ensured that the drill bit would not damage the bolts, restricting them from being used for testing. In order to correctly acquire all data need for the tensile testing, proper training was received by this group on the use of the MTS machine when it is configured with and Optim MegaDAC date acquisition system. During training for this machinery certain practices were noted to ensure safety while testing, which included, but not limited to, the emergency “stop” button, the release of gauge pressure on components, and the significance of proper lab attire. The students also had to learn how to use the Optim MegaDAC software in order to apply the desired load/displacement history to the test specimen, to automate the procurement of test data acquired by the different electronic transducers connected to the different channels of the data acquisition system, and to process, save and display this data in real-time as the test is being conducted.

Although this group could not do the T-stub connection test with rubber pads due to time limitations, the procedure, design, setup, and analysis of future testing was established and verified. In order to fully understand the deformation capability and yielding characteristics of T-stub connection components, the load deformation characteristics of the material used for each component of the connection was evaluated. The results of the aforementioned tests will be
helpful in understanding the behavior of the total connection and hopefully in identifying the contribution made by each connection component. All bolts to be used for the future testing program were strain gauged and calibrated, and all steel tension coupon tests for T-stub and test beam materials were performed, and values reported for yield strength, ultimate strength and modulus of elasticity. Finally, the test equipment needed to conduct the shear tests on neoprene rubber pads was designed, fabricated and tested. Value of modulus of shear was determined for the rubber pad proposed to be used in future tests. Hopefully, the results of the whole material testing program conducted and full-scale connection test set-up fabricated and erected in this REU project will give a head start to the researchers who will be involved in the proposed future testing.

Photographs showing the test setups and equipment used by the students on the project are shown in Figures 4 to 6.

2.3 Project # 3: Energy Dissipating in Steel Coupling Beams Involving Splice Joint Coupled with Elastomer

In this REU project the participants conducted an experimental pilot study to explore the concept of splicing the beam at the center with a small beam, called the “fuse,” which yields in shear when the shear walls are subjected to lateral loads caused during an earthquake. Thus, this strategy advocates the use of non-invasive and low-cost rehabilitation after the earthquake has ceased. In order to capitalize on both of these fronts, it is proposed that a piece of infrastructure be strategically placed to succumb to the effects of the applied shear force. This piece is placed in an area that can be easily accessed so it can be replaced with very little destruction of the surrounding structure.

In an effort to further increase the energy dissipation characteristics of the coupled shear wall system, neoprene elastomeric pads were also added in the project. These pads were placed between the splice plates and the fuse beam, both on the web and the flanges. The motivation for using neoprene elastomeric pads is their excellent energy absorption and damping capabilities. These properties may help to increase the efficiency of the fuse beam in the shear wall system, which was explored.

In this project, the energy dissipation capacity of the fuse beam, with and without the use of neoprene elastomeric pads was tested. The objectives of these tests were to compare the energy dissipation characteristics with and without the neoprene elastomeric pads and to determine the hysteretic response (load versus deformation) for both cases. The scope and research tasks included the following:

- Select a beam size and design its splice detail keeping in mind the maximum available actuator load capacity, and such that yielding in the fuse’s splice joint can be achieved before reaching the maximum actuator load.
- Conduct tension tests on coupons of the steel material used in the fuse, and shear tests on coupons of the neoprene elastomeric pads used. The mechanical specifications for steel products are noted in ASTM A370-02 and the standards for testing steel products are noted in ASTM E8-96a. Proper gripping pressure, loading rate, data collection and stress/strain...
interpretations are also specified for the purposes of standardizing the tests. In both of the tests, all appropriate standards were followed.

- Fabricate, assemble and test the splice beam connection by using the actuators to subject it to cyclic loads until yielding or failure occurs. Two tests were proposed to be performed, but only one test was conducted during the REU Site, and the specimen for the second test was fabricated and made ready.
- Repeat the test using neoprene elastomeric pads sandwiched between the splice plates and beam to check if energy dissipation is enhanced by the pads. Two tests were proposed to be performed, but only one test was conducted during the REU Site, and the specimen for the second test was fabricated and made ready.
- Compare the results of the two types of tests (with and without neoprene elastomeric pads). Identify the reasons for the differences in the performance under cyclic loads. Identify how performance can be further enhanced.
- Make recommendations for a comprehensive study to characterize the behavior of splice coupled beams with or without neoprene elastomeric pads.

This project consisted of several coupon tests and one main test. Due to time constraints only one of the six scheduled coupon tests were preformed. This was the tensile test of the coupon that represented the web of the fuse. Grade A36 steel was selected for the fuse beam material, and it was theoretically designed to yield in shear before the maximum capacity of the load actuators got exhausted. If the yield strength of the fuse steel were significantly greater than the expected value of 36 ksi for A36 steel, then it would have been a problem. Based on the one coupon test conducted it was found the yield stress of the fuse material was found to be 38 ksi, which was acceptable. After this verification, the fuse beams were fabricated using the steel supplied by the vendor. The coupon test was performed using the Minnesota Testing System (MTS) machine in the High bay Laboratory at the University of Cincinnati Main Campus. It was exactly the same as the coupon tension tests conducted by Project # 2. Also, this group conducted the shear test on the neoprene elastomeric pads along with this group using the MTS machine.

The fuse beam test was done at the Large-Scale Structural Testing Facility at Center Hill. The test set-up configuration used is shown in the photographs attached at the end. Two actuators were placed at opposite ends of an A-992 W14 x 61 beam, which were 32 ft apart. They were programmed to oscillate in opposite directions in order to create the necessary shear forces with no moment in the center of the connection, where the fuse beam was placed. The beam was supported at two locations equidistant to the center with a total span of 8 ft. Rods were used as contact surfaces to give the pins support and freedom of movement at these locations. The rods were milled and greased to eliminate friction between the beams and the supports. The supports were mounted on an adjustable frame that allows for fabrication tolerances and gives an exact bearing at the supports. The beam was braced at four locations. These braces prevented the coupling beam from experiencing any out-of-plane horizontal movement. In order to adjust for the tolerances experienced during fabrication, a few shims using scrap steel were clamped onto the braces. On the sides of the braces and the supports, two diagonal braces were placed as extra leverage against falling over. The head of the actuator and the bolts used in the splicing of the fuse were also pre-tensioned to the exact level using Direct
Tension Indicators (DTIs). The bolts on the splice plates were tightened to slip critical specifications.

The fuse was a built-up welded I-section consisting of two flange plates 3/8 in. thick, and one web plate 1/8 in. thick. The splice plates included two flange plates, which was 1/2 in. thick, and 2 web plates, one for each side, which was 3/8 in. thick. They were bolted together by 12-No. of 5/8 in. diameter A-325 bolts on the flanges, and 18-No. of 5/8 in. diameter A-325 bolts on the webs. The ½ in. thick plates provided the necessary rigidity to the flanges and helped the web to stiffen under the expected load the test fuse specimen and the support beams would have been subjected to. Two kinds of fuses were designed; two with two stiffeners and two with three stiffeners. One of each kind will be tested with neoprene elastomeric pads. Due to time constraints, only the fuses with two stiffeners were tested in the REU Site.

Neoprene elastomeric pads were only used in one test. They were installed between the splice plates and the beam on both sides of the web and on the flanges. DTIs were used to indicate pretension forces in bolts. The bolts were tightened until the pads expanded considerably. Because of the enhanced elastic properties of the pads, the bolts were not able to be tightened completely. There still was some give in the connections after being pre-tensioned. It was noted by the REU participants, it is important that the bolts with pads are not over tightened. If they are tensioned over the compressive limit of the rubber, they become plastic, and as the cyclic loads are applied the pads will be subjected to a force much greater than they can withstand and they may start shredding.

For each test several measurements were taken to characterize the behavior of cyclic loading on a coupled beam with a fuse implanted in the center. Mounted to each actuator was a load cell that measured the amount of applied force on the beams. Also connected to the side of each actuator was a wire potentiometer that measured the displacement of the actuator as it applied its load. Located 48 in. towards the fuse from each actuator was another wire potentiometer. These potentiometers were used to measure the displacement of the beam and to make sure the movement was linear between the pinned support and the actuator. Four strain gauges were placed along the top of the beam, two strain gauges at each pinned support and two strain gauges 12 in. from the edge of the coupling beam. These gauges were placed to assure that the coupling beam remained in the elastic region. Strain rosettes were placed at the neutral axis of the fuse and along the vertical center of the splice plates. Rosettes were placed at three points to compare the horizontal, vertical and diagonal forces exerted on the coupling beam and the fuse. Two of the three points are 12 in. from the edge of the coupling beam with the other point being in the center of the fuse. These rosettes were placed to assure that the coupling beam did not assume plasticity and that the fuse did.

During testing the two actuators oscillated in opposite directions. The actuators were set for displacement control so the beams did not experience any unnecessary forces. The displacement of the beam was recorded in radians, which can then be converted to inches to show the displacement of the actuator. The rotation was increased incrementally and repeated thrice in the beginning and twice after 0.10 radians were reached. The data was read into a text file and saved as the test progressed. The first period of each rotation was input into a MS Excel file. This was done so that the load versus displacement graphs can be reviewed to make sure the tests are...
progressing satisfactorily. The maximum strain value read was also noted for each cycle to ensure that the fuse yields before the coupling beam. The tests were stopped either when the fuse produced fatigue point due to buckling or when the coupling beam has nearly reached its elastic limit.

The first test included a fuse beam with two stiffeners and without neoprene elastomers. In this test, the fuse buckled at a rotation of 0.28 radians. The test was continued so the behavior of the fuse afterwards could be observed. The test was stopped at 0.32 radians, at which point the fuse had gone well into the plastic range. The fuse showed two points of fatigue where the direction of the buckling changed the most. The web of the fuse failed in shear as expected, while the flanges remained in good condition. The bolt holes on the beam and the fuse showed no signs of bearing or other major damage, so the slip critical connections functioned well. The second test consisted of the fuse beam with two stiffeners and with neoprene elastomers. This test was stopped at a rotation of 0.40 radians; at the point that the coupling beam neared its elastic limits. The fuse did not buckle but the strain readings reflected that it had reached plasticity, though the apparatus was still picking up load. The neoprene elastomeric pads appeared to perform well but the bolts did begin to make popping noises as the cycles neared the zero points. These noises sounded like the bolts were slipping but the load versus displacement graphs did not show any signs of slipping and the boltholes suffered no damage. The neoprene elastomeric pads performed well but got wedged in the gaps between the fuse and the coupling beam causing them to be shredded as the test progressed.

The results of the two tests were compared by the group. Both tests performed well. When compared to each other it seemed that the fuse without neoprene elastomeric pads was able to dissipate more energy than the fuse with rubber pads. Though upon closer examination, it was noted that the fuse of the first test buckled severely at the conclusion of the test, whereas in the second test the fuse did not reach the buckling phase. All in all, the tests were a success. The fuse failed in shear with no damage to the flanges, boltholes or the coupling beam. The neoprene elastomeric pads prevented the fuse from buckling, although it did yield. The coupling beams suffered no damage other than the scratching of the paint in both tests. For the load versus displacement plots recorded for both east and west sides, the second showed an increase in displacement at the expense of lost load when compared to the first test. But, the system was still picking up load in the second test when it was concluded, so a general conclusion could not be formulated at this point in time. Comparing the load versus shear strain plots for both tests, the results showed that the incorporation of a fuse into a coupling wall system dissipated energy in a way that is ideal. The graph for the first test showed wide hysteresis loops that increase significantly until the point at which the fuse yielded. At that point, the loops still increased in area, but at a much smaller rate than before. This indicated that the fuse had indeed reached plasticity and was unable to dissipate energy as efficiently. The graph for the second test showed the same thing, but without the behavior when buckled. This lack of information prevented comparison between the two tests to be made with regards to their behavior after yielding. The group concluded that further tests need to be conducted with coupling beams significantly stronger than the ones used in the study in order to fully understand how neoprene elastomeric pads affect the fuse connection.
As described above, several types of specialized equipment were used by the REU participants in the execution of this project. The students had to be trained on how to use and calibrate these equipments properly, in particular one of the REU participants spent much of her time figuring out how to hook up various types of instruments to a recently purchased data acquisition system, and configuring the use of its software for each. The data acquisition system used by the group was different from the one used by the other two groups. The tension coupon test on steel materials and the shear tests on neoprene elastomeric pads required the use of the MTS machine, which had its own data acquisition system. The students learned how to perform these important tests using this data acquisition system. The students also handled mechanical equipments like drills, grinders, pneumatic wrenches, etc.

Photographs showing the test setups and equipment used by the students on the project are shown in Figures 7 and 8.

3. Evaluations Conducted and Results

On the last day of the Site each group gave a one-hour presentation to a panel of external judges, who evaluated the presentations as well as their project reports. The judges consisted of three practicing civil engineers, and the faculty member who earlier had presented the photography workshop to the students. After each presentation, the judges filled-out two separate evaluation forms, one to evaluate each participant’s presentation, and the second to evaluate each group’s Technical Report. The evaluation results provided by the judges for each student presentation was averaged and is presented in Table 1 for each group. The evaluation results provided by the judges for the Technical Report of each group are presented in Table 2.

The results presented in Tables 1 and 2 clearly indicate that all the groups performed equally well; all earned a rating between 4.00 and 5.00 (where 5 = Excellent and 4 = Very Good), both for their presentation and report writing. The judges were very impressed with the high quality of work done in the limited time period (two months). They were also impressed by the way the students presented their work using computer-based multi-media graphics with animation, video clips, and scanned photographs. After the three groups had presented, the judges deliberated, and considered the written Project Report, oral presentation, questions and answers, and poster (see Figure 9) in choosing the award selections. They selected Project 1 group, which worked on the Modeling the Behavior of T-stub Connections, to be the winner of the “Best Project Report.” They selected Project 1 group also to be the winner of the “Best Presentation.” Each participant was also awarded a certificate showing his or her participation in this NSF REU Site.

Each student participant was asked to give a written narrative evaluation of his or her experience, and mail it within two weeks after they left. Besides the narrative evaluation, each participant filled out a separate questionnaire on the first day and the last day of the REU Site to assess the success of the REU experience provided. In general, all students expressed great satisfaction with the experience and commented that they would highly recommend a similar experience to their friends. The participants were given instructions on the work expected of them during September 2003 to May 2004, after they return to their home institutions. Each participant was required to make a presentation at their host institution, a report of which had to be supplied by their academic advisor.
4. **Summary Comments**

Universal lessons learned by each group included the following:
1. The identification of important parameters to be studied and appropriate testing procedures.
2. How to vary these parameters within practical limits.
3. Selection of appropriate parameter combinations so that the effects of each parameter can be isolated.
4. Manufacturing of test specimens.
5. Design and fabrication of test apparatus.
6. The importance of testing procedures and data recording.
7. Data synthesis.
8. Regression analysis of test data to develop prediction equations.
9. Teamwork and collaborative learning (between participant and participant, participant and graduate assistant, and participant and faculty mentor).
10. Use of visual aids in communicating the test responses.
11. Writing and presentation of technical reports.

It is noted that the key experience gained by the students was how to organize and conduct a research project with defined objectives. Every opportunity was provided to nurture and challenge the curiosity and creativity of the participants.

5. **Acknowledgment**

The author would like to acknowledge the financial support provided by NSF for this REU Site (Award No.EEC-0196371), and cost sharing provided by UC. The author would also like to acknowledge the following faculty members who mentored the REU participants besides the author (Project Director): Dr. James A. Swanson, Assistant Professor (for Project 2), and Dr. Bahram Shahrooz and Dr. Gian Rassati (for Project 3), Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, Ohio. The following graduate students acted as the Graduate Student Mentors: Sridhar Sadasivan (for Project 1), Vinod Thimmapura (for Project 2), and Ratnadeep Kundu (for Project 3), M.S. students, Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, Ohio; and Mr. Robert E. Muench who served as the Lab Technician for the project.

6. **Bibliography**

ANANT R. KUKRETI

Anant R. Kukreti is a professor of Civil Engineering and Head of the Department of Civil and Environmental Engineering at University of Cincinnati. He was a faculty member at the University of Oklahoma for 22 years before moving to University of Cincinnati in August 2000. He has won numerous teaching awards, which include the Burlington Northern Foundation Teaching Award, Regents Award for Superior Teaching, ASEE Midwest Section Outstanding Teaching Award, and the ASEE Fluke Corporation Award for Innovation in Laboratory Instruction. At University of Oklahoma he also received the David Ross Boyd Professorship.
## Table 1. Judges Evaluations of Individual Presentations

<table>
<thead>
<tr>
<th>Group</th>
<th>Attitude</th>
<th>Organization &amp; Presentation Emphasis</th>
<th>Clarity of Presentation</th>
<th>Use and Quality of Visual Aids</th>
<th>Response to Questions</th>
<th>Total Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1: &quot;Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections:&quot;</td>
<td>4.89/5.00</td>
<td>5.00/5.00</td>
<td>4.78/5.00</td>
<td>4.33/5.00</td>
<td>4.44/5.00</td>
<td>4.68/5.00</td>
</tr>
<tr>
<td>Project 2: &quot;Novel Steel Frame Connection with Damping Capability&quot;</td>
<td>4.33/5.00</td>
<td>3.44/5.00</td>
<td>3.33/5.00</td>
<td>4.33/5.00</td>
<td>3.00/5.00</td>
<td>3.69/5.00</td>
</tr>
<tr>
<td>Project 3: &quot;Next Generation of Steel Coupling Beams with Energy Dissipation Device&quot;</td>
<td>4.78/5.00</td>
<td>5.00/5.00</td>
<td>5.00/5.00</td>
<td>4.67/5.00</td>
<td>5.00/5.00</td>
<td>4.89/5.00</td>
</tr>
</tbody>
</table>

**KEY** 5= Excellent  4 = Very Good  3 = Good  2 = Fair  1 = Unsatisfactory

### Project 1: "Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections:

**Participant 1:**
1) The group worked very good together
2) Well prepared, very professional. Suspect his leadership was very important to success of project.
3) Good teamwork. Joe clearly the leader, at least in the presentation. Very comfortable with speaking role. Confident. Understood and was very good in describing/presenting fundamental principals of their project. Clearly devoted to understanding the project.

**Participant 2:**
1) Very conversant on topic. Confident speaker. Did a good job explaining his interpretations of the results.
2) Understands the analysis and responded well when questioned. Suspect Kevin was very critical with fabrication of physical testing. Understood actions and good explanations.
3) The group worked very good together.

### Project 2: "Novel Steel Frame Connection with Damping Capability"

**Participant 4:**
1) Did a good job of leading presentation. Organized and logical, but not sure if there is an understanding of design aspects with connection.
2) Animations during presentations were good.
3) He did a good job defining and having audience understand the objective of this project. Was prepared with presentation but spoke to screen often instead of audience. Should have had some conclusion, even with limited experimental data.

**Participant 5:**
1) Appeared to be leader of the group. He understood and communicated well the anticipated benefits of elastomer but seemed to lack understanding of entire project and how all of the pieces of the project fit together.
2) Very good graphics. Seemed to be the most technical with most understanding of theoretical work.
3) Good animations.

**Participant 6:**
1) Good presenter. Suspect that she does not see how analysis of connection should be made. Did not answer questions well.
2) nice animations.
3) She was direct in her presentation. Would be good if she could add unique aspects of
Table 2. Judges Evaluations of Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Organization</th>
<th>Method of Analysis</th>
<th>Critical Path</th>
<th>Synthesis of Test Data</th>
<th>Goal Achievement</th>
<th>Total Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1: &quot;Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections:&quot;</td>
<td>5.00/5.00</td>
<td>5.00/5.00</td>
<td>4.75/5.00</td>
<td>5.00/5.00</td>
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<td>3.15/5.00</td>
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<tr>
<td>Project 3: &quot;Next Generation of Steel Coupling Beams with Energy Dissipation Device&quot;</td>
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<td>4.50/5.00</td>
<td>5.00/5.00</td>
<td>4.50/5.00</td>
<td>4.75/5.00</td>
<td>4.75/5.00</td>
</tr>
</tbody>
</table>

KEY  
5 = Excellent  4 = Very Good  3 = Good  2 = Fair  1 = Unsatisfactory

Project 1: "Mathematical Modeling of Monotonic and Cyclic Behavior of T-stub Steel Connections"  
1) The group worked very good together  
2) Excellent work and presentation. Spread out work and responsibilities. Understood the basis of project and followed good logical path to completion.  
3) The group worked well as a team. Persistent to gather results. Exciting project. Built on previous work by Drs. Kukreti and Swanson.
| Project 2: "Novel Steel Frame Connection with Damping Capability" | 1) Presenters lacked much enthusiasm in their good work. PowerPoint had some good animation which helped with their discussion. It is unfortunate that time ran out and they were unable to test with neoprene. Needed some conclusions.  
2) This group seems not having worked as well together as a team as group 1 did. During the presentation they made good use of visual aids (animation in PowerPoint). Unfortunately, the group ran out of time. It would be very interesting to see results for the use of elastomeric bearings.  
3) Difficult project to see to end since testing was not completed. Not sure that they understand how connection works nor objectives with neoprene connection. Much of same work from presentation #1. |
|---|---|
| Project 3: "Next Generation of Steel Coupling Beams with Energy Dissipation Device" | 1) Excellent job done.  
2) Tremendous job. The group worked well as a team. They were focused and worked hard to achieve their goal. Promising results.  
3) Good graphics. Expected more analysis of data from test, but tests are still going on. Suspect they spent extraordinary amount of time with test. Did a very good job, just didn't continue. Time more probably due to circumstances beyond their control. |

Figure 1. REU Participants Preparing Tension Coupon Specimens for Testing: Project #1
Figure 2. REU Participant and Graduate Mentor Setting-up the Beam Brace Supports: Project # 1

Figure 3. REU Student Positioning Clamps to Hold the Linear Variable Displacement Transducer (LVDT) in the T-Stub Connection: Project # 1
Figure 4. REU Student Using the Lathe Machine to Drill a Hole in the Bolt for Strain Gauge Installation: Project # 2

Figure 5. Neoprene Rubber Pad Shear Shear Test Specimen Installed in the MTS Machine: Project # 2
Figure 6. Final Connection Test Set-Up at the Center Hill Testing Facility: Projects # 1 & 2

Figure 7. Fuse Installation Done by a REU Participant, Faculty Mentor and Graduate Mentor: Project # 3
Figure 8. REU Participants Installing Strain Gauges: Project # 3

Figure 9. T-Stub Behavior Modeling Group (Project # 1) with their Poster