Smart Patch for monitoring the integrity of steel frame joints

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ABSTRACT

Acellent Technologies, Inc. developed a smart structural health monitoring (SHM) sensor network that can autonomously assess in real time the structural stability of buildings. The sensor network uses piezoelectric actuators and sensors to characterize damage in, and monitor the rigidity of components of the building primary structure. Additionally, temperature sensors are integrated into the proposed sensor network to monitor the temperature of the structural components. Acellent's existing sensor network SMART Layer technology was used as the basis for the proposed development. The modifications to our existing technology included a redesigned sensor/actuator arrangement, the development of a SmartDAQ sensor package with the required sensor and electronics, and additional software that provides a map of the structural damage, temperature and rigidity information. This will be useful to provide a real time assessment of the building structural integrity. The data will be available for display to provide and early warning to first responders and emergency personnel to ensure their safety prior to entering the building.

Keywords: Structural Health Monitoring, SMART Layer, Piezoelectric, Actuator, Sensor, Building Safety

1. INTRODUCTION

The collapse of the World Trade Center Twin Towers as a result of the terrorist attack on Sept. 11, 2001 and the subsequent loss of life of the New York City Fire Department personnel highlights the importance of developing methods for providing an early warning of serious structural instability or impending collapse to emergency personnel and first responders. The catastrophic collapse of the towers was caused most probably by a combination of the structural damage due to the aircraft impact and the high structural temperatures resulting from the burning jet fuel. This dramatically demonstrated that the construction of our multi-story office buildings are more susceptible to problems with structural stability than previously thought. The building techniques commonly used for these types of buildings utilize *Welded Steel Moment Frame* (WSMF) construction as shown in Figure 1 as the primary load bearing structure.

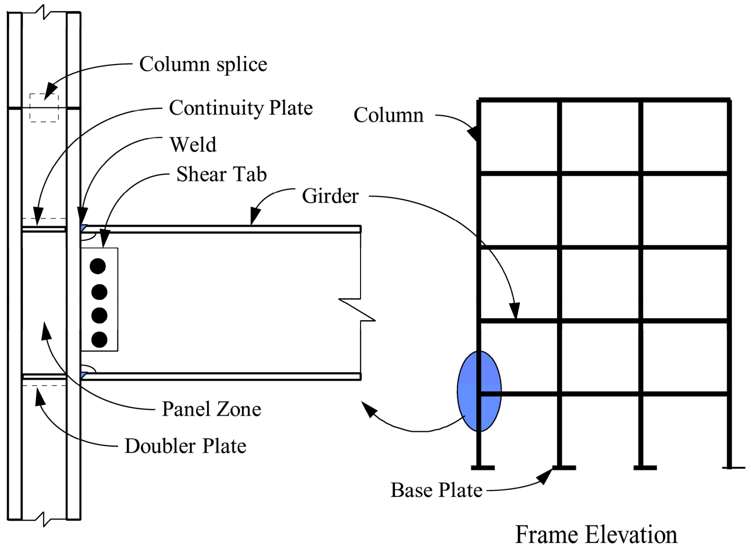

Fig. 1 Critical Beam-column Joint Elements of Welded Steel Moment Frame (WSMF)

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Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure,
and Homeland Security 2009, edited by H. Felix Wu, Aaron A. Diaz, Peter J. Shull, Dietmar W. Vogel,
Proc. of SPIE Vol. 7294, 72941B · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.816652

Studies of these types of buildings damaged during earthquakes, such as the Northridge Earthquake of January 17, 1994, have shown that the prequalified, welded beam-to-column moment connection commonly used in the construction of WSMFs is much more susceptible to damage than had been previously anticipated [1]. During earthquakes, the stability of moment frame structures depends on the capacity of the beam-column connection to remain intact and to resist rotations of the beams and columns with respect to each other. The prequalified connections are supposed to be ductile and capable of withstanding the repeated cycles of large deformation explicitly relied upon in the building code provisions for the design of these structures. But, a wide spectrum of unexpected brittle connection fractures did occur, ranging from isolated fractures through or adjacent to the welds of beam flanges to columns, to large fractures extending across the full depth of the columns. Damaged elements included girders, columns, column panel zones (including girder flange continuity and column web doubler plates), the welds of the beam-to-column flanges, and the shear tabs that connect the girder webs to column flanges. Severe connection fractures can result in significant risk of local collapse and life safety endangerment. Luckily, there were no such collapses of WSMF buildings in the 1994 Northridge Earthquake. But, unfortunately, a number of WSMF buildings did experience collapse in the 1995 Kobe Earthquake.

Search and rescue personnel are often unable to assess apriori the stability of the structure or determine the appropriate amount and type of structural hazard mitigation required to minimize risk to personnel. In order to reliably determine if a building has sustained connection damage, it is necessary to remove architectural finishes and fireproofing and perform nondestructive examination including visual inspection, magnetic particle testing (MT), liquid dye penetrant testing (PT), radiographic testing (RT), and ultrasonic testing (UT). This is an extremely time and labor intensive process that can not be used to support search and rescue operations after a catastrophic event such as a terrorist attack or earthquake. Even if no damage is found, it is a very costly process. For example, economic losses resulting from earthquake induced building damage include direct costs resulting from inspection to determine the extent of damage, engineering design fees, actual costs related to the structural repairs, demolition and replacement costs for architectural finishes and utilities (that must be removed to allow access for inspection and repair), and repair of damaged non-structural components, as well as indirect costs resulting from loss of use, interruption of business, lost income from rents that are not collected on spaces vacated during the repair period, and project financing costs.

Enormous benefits can be realized by using an advanced sensor network to monitor the welded beam-to-column moment connections in WSMF structures. An integrated structural health monitoring system (SHMS) would provide the following advantages over existing methods to inspect and assess the structural integrity of buildings:

- ✓ Real time assessment of structural stability and impending collapse
- ✓ Stand off mode allowing safer operation with less risk to emergency response personnel
- ✓ Map of structural damage and temperature to identify and locate hot spots
- ✓ Reduction of time to pin point location of survivors trapped in building
- ✓ Ability to communicate with survivors
- ✓ Reduced cost and time for structural inspections
- ✓ Improvement of structural reliability
- ✓ Minimization of catastrophic structural failure
- ✓ Convenience and automation of inspection

Just in the past several years, structural health monitoring has emerged from the research environment into initial applications in a wide variety of fields, from civil infrastructure to aerospace. Structural Health Monitoring (SHM) technology is perceived as a revolutionary method of determining the integrity of structures involving the use of multidisciplinary fields including sensors, materials, signal processing, system integration and signal interpretation. The core of the technology is the development of *self-sufficient* systems for the continuous monitoring, inspection and damage detection of structures with minimal labor involvement. The aim of the technology is not simply to detect structural failure, but also provide an early indication of physical damage. The early warning provided by an SHM system can then be used to define remedial strategies before the structural damage leads to failure.

2. TECHNICAL APPROACH

The SMART technology offers a solution to the current problems associated with inspecting welded beam-to-column moment connections in WSMF structures. By applying techniques that utilize Acellent's SMART Layer® concept, sensors located on and around the beam-to-column connection can autonomously assess the integrity and long-term durability of the joint (Fig. 2).

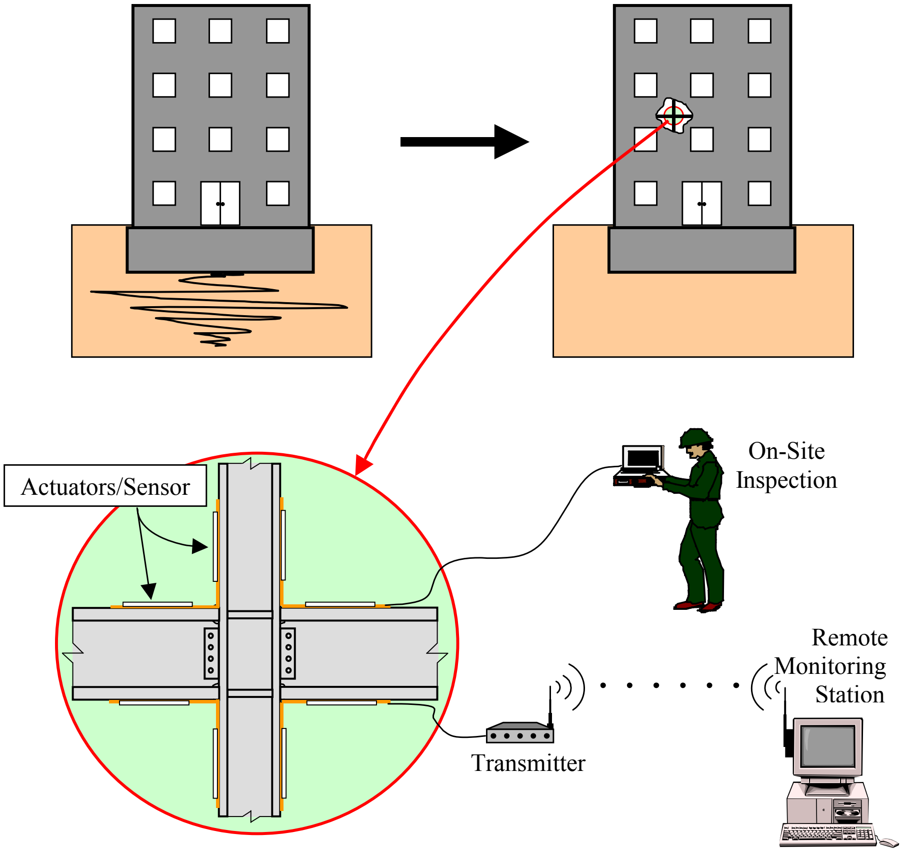
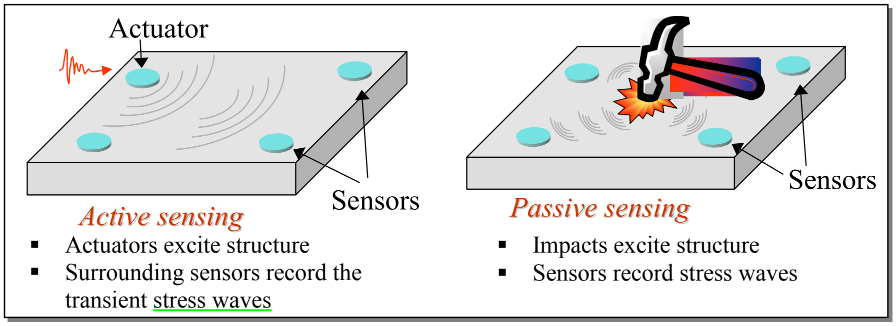


Fig. 2 Smart Patch Joint Monitoring System Development Model

The SMART Layer technology is currently available for both *active* and *passive* sensing capabilities using piezoelectric sensors (PZT). In Active Sensing Mode, each piezoelectric element can be used as an actuator to excite the structure while the neighboring sensors listen. The sensor responses can then be interpreted in terms of damage location and size or material property changes within the structure. In Passive Sensing Mode the SMART Layer can be used as a continuously monitoring sensor network to "listen" for impact events. Both Modes permit real-time structural analysis and evaluation along with constant collection of structural data and information while the structure/vehicle is in service. Figure 3 shows the working concept of active and passive sensing.

The SMART Layer technology has been successfully demonstrated for detecting damage in structures. The technique utilizes embedded piezoelectric devices to emit diagnostic signals to the neighboring piezoelectric sensors. By measuring the changes in sensor measurements relative to a constant diagnostic signal, cracks emanating from fastener holes have been successfully detected on aircraft structure. Similar techniques have been used with SMART Layers to detect impact-induced delaminations and cracks in composite and aluminum plates, respectively [2-8].



- Actuators excite structure
- Surrounding sensors record the transient stress waves

- Impacts excite structure
- Sensors record stress waves

Fig. 3 Active and passive sensing methods

3. POTENTIAL APPLICATIONS

The Smart Patch system can be used in a number of applications ranging from buildings, bridges to off-shore structures. Acellent has identified several applications that can make full use of this technology, such as:

A) Monitoring of buildings in earthquake prone regions: Buildings in regions such as California are highly susceptible to damage due to earthquakes. There are hundreds of identified faults in California; about 200 are considered potentially hazardous based on their slip rates in recent geological time (the last 10,000 years). More than 70 percent of the state's population resides within 30 miles of a fault where high ground shaking could occur in the next 50 years. The National Earthquake Information Center (U.S.) reports 12,000-14,000 earthquakes a year around the world, or 35 a day. Throughout the world, there are one "great" (magnitude 8.0 or more), 18 "major" (7.0-7.9), 120 "large" (6.0-6.9) and 1,000 "moderate" (5.0-5.9) earthquakes in an average year. Each year, California generally gets two or three earthquakes large enough to cause moderate damage to structures (magnitude 5.5 and higher). Determining the structural integrity of buildings after an earthquake has always been a challenge. The Smart Patch system can be used to assess the integrity of buildings and ensure the safety of rescue personnel.

B) Monitoring of bridges and off-shore structures: While more than 40 percent of the over 500,000 bridges nationwide are either structurally deficient or functionally obsolete mainly because of aging, rehabilitation of these bridges becomes the only feasible solution. Among a variety of rehabilitation technologies available, externally bonded Carbon Fiber Reinforced Plastic (CFRP) composite strips have been demonstrated to be one of most promising method for repairing and/or reinforcing damaged structures in a large scale to prolong their service lives and avoid loss of lives and assets. Recently, Acellent's Structural Health Monitoring (SHM) systems have been used as nondestructive evaluation tools for detecting the disbonds between composite repair patches and deck slabs of concrete in bridge rehabilitation (Fig. 4) [15]. In addition to monitoring of bridge repairs, damage prone areas on bridges and off-shore structures such as oil-rigs are also potential applications that can utilize the Smart Patch system.

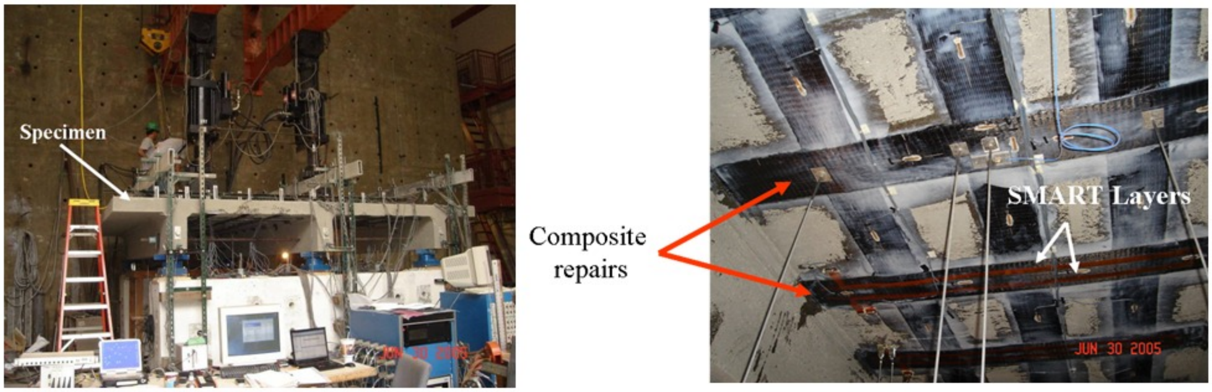


Fig. 4 Acellent's SHM systems used for evaluating composite bridge repairs

4. PROOF OF CONCEPT AND LABORATORY EXPERIMENTS

4.1 Internal Beam-column Joint Coupon Testing

A) Internal Frame Joint Specimen Fabrication

Acellent started the development of the Smart Patch System by first obtaining test specimens of typical Welded Steel Moment Frame joints. The specimen, a cross-section of 4"x6", length of 4 ft, Beam and Column Joint, Hot Rolled A36 Steel under AISI standards, was fabricated from the machine shop and layout is as in Fig. 6.

B) Sensors and Configuration

Piezoelectric transducers of size 2"x3" with a thickness of 0.1" were obtained from appropriate vendors. These were mounted on the steel test specimen as shown in the figure below. Eight transducers were mounted for preliminary testing, two on each leg. A set of baseline signals was taken with the sensors using existing data acquisition hardware.

C) Testing for monitoring of joint rigidity

A test-setup was designed to deform the test article instrumented with the sensors. A picture of the test set-up is shown below. The goal was to determine the rigidity of the specimen. To do this the specimen needed to be bent under stress. In order to ensure a change in rigidity, cuts were made in the test specimen at the joints. Bending was accomplished by using chains around the test specimen and a base girder. Force was applied using a 30 ton jack and measured using the force gage (Fig. 6). The distance between the edges of the test specimens was measured at set force levels.

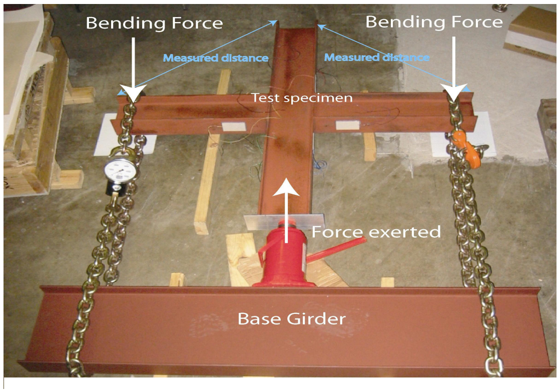
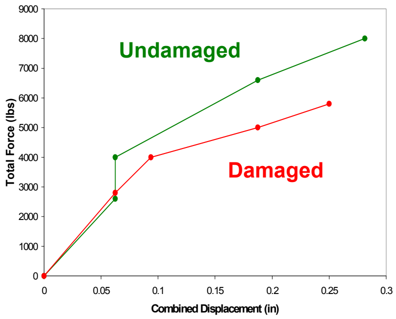


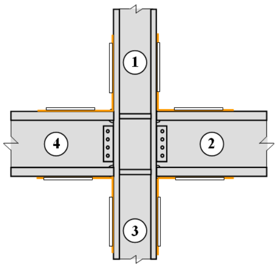
Fig. 5 Welded Steel Moment Frame Specimen and Testing Method

D) Test Results

As stated above, a measure of the joint rigidity was obtained by applying a load to the specimen and measuring the induced displacement, d, between the corners of the frame. This was done before and after adding damage (cuts at the joint) to the specimen. Figure 6 shows the load-displacement curves for the undamaged and damaged frame. The chart clearly shows a loss in joint stiffness after being damaged.

Figure 7 shows the signal energy ratio computed from the experiment of bending moment tests. Sensor data was also collected before and after inducing damage in the structure. On one leg, two piezoelectric actuators, with opposite polarity, were excited by a 4 kHz sine wave pulse. The transmitted signal energy for actuating and sensing transducer pairs 1 → 2, 1 → 3 and 1 → 4 was calculated for the damaged state. These values were normalized against the transmitted signal energy from the undamaged state. As can be seen, the signal energy ratios for actuator and sensor pairs 1 → 2 and 1 → 4 are reduced (below 1.0), while the signal energy ratio for actuator and sensor pair 1 → 3 is increased (above 1.0). This is due to the fact that as damage accumulates, and the stiffness of the joint is reduced, less energy can be transmitted from the column to the beam, resulting in lower signal energy ratios for actuator and sensor pairs 1 → 2 and 1 → 4. Also, since less energy is transmitted to the beam, more energy stays in the column, resulting in a higher signal energy ratio for actuator and sensor pair 1 → 3.





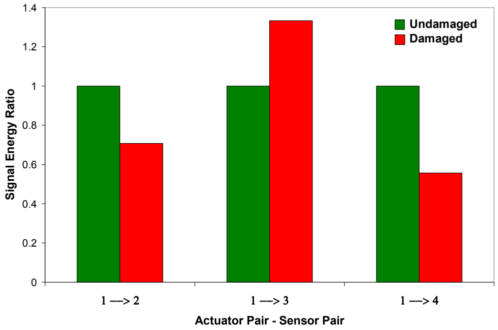


Fig. 6 Displacement in the undamaged and damaged state

Fig. 7 Signal energy ratio for signal paths

4.2 External Beam-Column Joint Component Testing

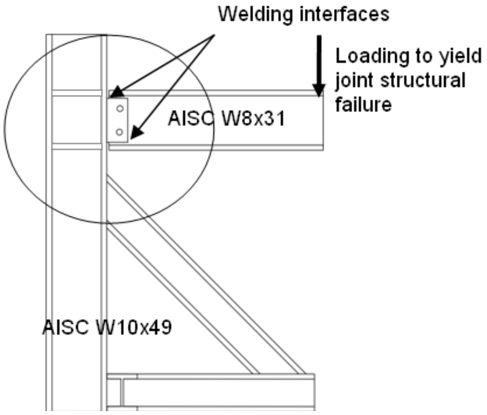


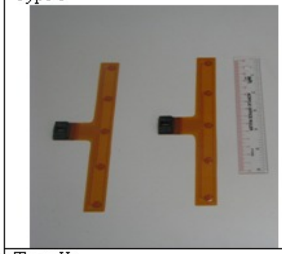
Fig.8 Beam-column Joint Specimen

A) External Joint Component Manufacturing

Acellent worked with Leighton Group Engineering Corp. and Testing Engineers, Inc. to fabricate an external beam-column joint specimen for testing of Smart Patch system. The beam member is following American Institute of Steel Construction (AISC) W-8x31 wide beam specification, and the column is W-10x49. The joint interfaces between beam and column were completely penetration grooved welds and the work was done by certified welders. The design of specimen is shown in Fig. 8.

B) Sensors and Configuration

Figure 9 shows the types of SMART Layers for sensors and configuration. Circular piezoelectric transducer and sensor with a diameter of ¼" and a thickness of 0.1" was selected to be embedded in SMART Layers for external beam-column joint specimen based on its optimal signal performance in the earlier coupon testing. Two types of Layers were used: Type 1, T-shaped with 5 PZT disks and, Type 2, a stripe with 4 PZT disks embedded. Two pairs of Type 1 SMART Layers were mounted for monitoring the welded interfaces between beam and column. One pair of Type 2 SMART Layers were installed in between the column and the shear resisting bolted plate in the middle of the beam section. The last pair of Type 2 SMART layers were mounted for detection of damage near the beam web and column's interface. Another pair of Type 2 were mounted on the column web surface for monitoring the rotation of column near joint center. The baseline signals were taken using ScanGenie^{TM} system [17].

Smart Joint Sensor Layer Type	Description
Type I 	• T-shaped (2"Hx8"L) Layer • Connector in the middle • 5 PZT Sensors, ¼ in Diameter Circular Disk • Spacing 1.75" • Installed on the Flange Surface of I-Beam • Monitoring the welded interface between the beam and column connection
Type II 	• Stripe Layer (8" L) • Connector in the end of stripe • 4 PZT Sensors, ¼ in Diameter Circular Disk • Spacing 1.5" • Installed on the surface of Web of I-Beam • Used for 1) Monitoring the welded interface between the beam web and the flange of I-beamed column 2) Monitoring the deflection (plastic hinge behavior) of the web section of column

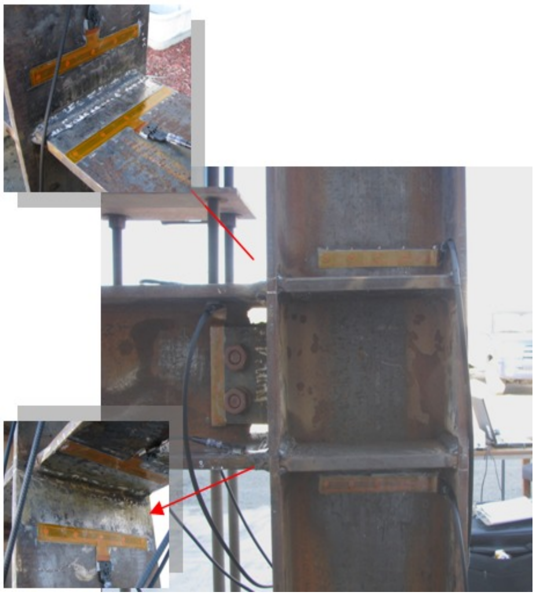
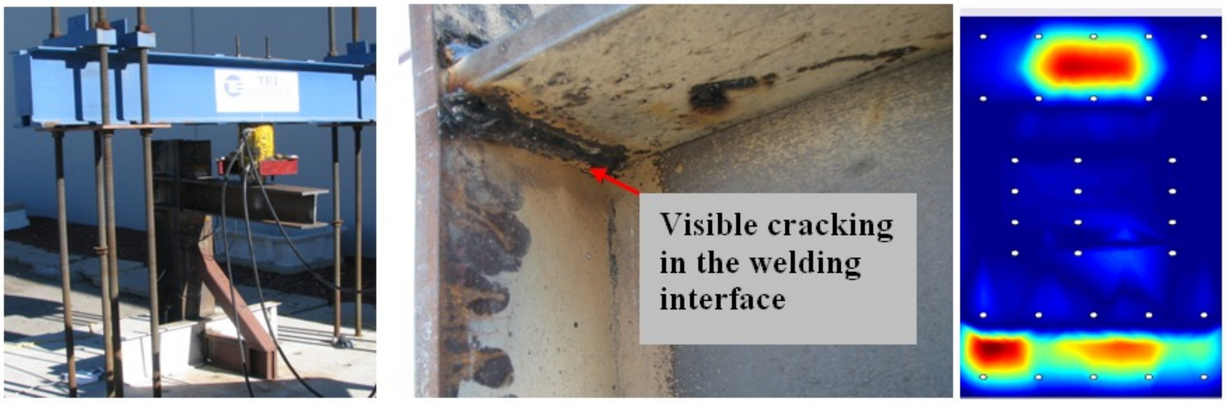


Fig. 9 Smart Patch Sensor Installation for External Beam-column Joint Component

C) Testing for monitoring of joint rigidity

The specimen testing was performed in the certified test center, Testing Engineers, Inc., in San Leandro, CA. During the testing, we applied the loading to the beam element to cause the maximum bending moment in the beam-column joint. The loading for the test was applied with an initial loading of 20 kips incremented by 10 kips at each interval (Fig. 10(a)). The structure eventually failed by the loading to 114 kips, right after the loading of 110 kips. The data were taken at the loading of 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 114 kips. At this load, we checked the structure and found a crack in the interface of stiffener and the flange of the column section as shown in Fig. 10(b).



(a) Loading Device (b) Cracking in the welding interface (c) Damage Display in Software

Fig. 10 External Beam-Column Joint Component Testing and Damage Image Display from Acellent ACESS software

D) Test Results

Acellent Software Suite (ACESS) is the standard software developed in the Smart Package of Acellent's active structural health monitoring system [17-18]. This is system can perform a data management platform for piezoelectric acoustic ultrasound sensors. With the design of signal processing modules and damage detection algorithm, we can quantify the damage degrees in terms of damage index. Fig. 11 shows the results using Total Signal Energy (TSE) of scatter signal in the first-mode arrival time window (FAW) as known as time window analysis.

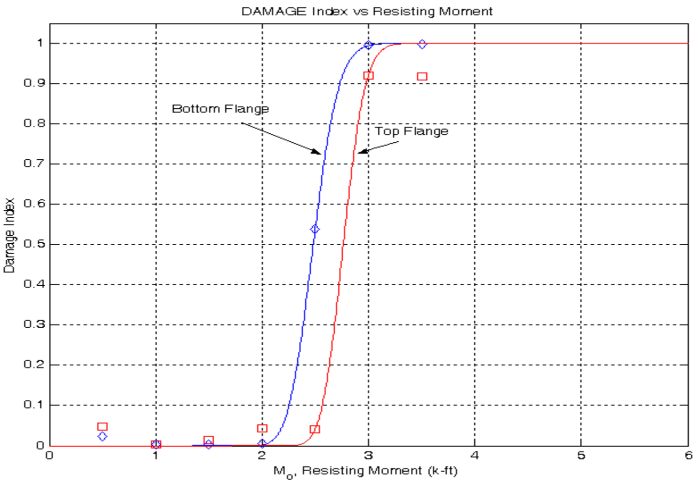


Fig. 11 Quantitative Diagnostics Result from Smart Patch ACESS software

5. CONCLUSION

Current study is focused on determining the feasibility of the Smart Patch system proof of concept and establishment of the system design architecture. The current achievements are:

- Using Acellent acoustic ultrasound technique to assess WSMF beam-column joint's progressive damage due to exceeding bending moment
- Smart Patch sensors can detect the damage, and monitor the progress of damages such as plastic hinge behavior in column and the growth of crack length in the welding interfaces
- Current system, comprising of the ScanGenie hardware and software is validated in full scale structure subcomponent.

- Structural integrity function can be determined by (interpreted from) the rigidity assessment of beam-column joints by evaluation of damage index from the Smart Patch System, in principle.

The system validation has been achieved and a practical and easy-to-use prototype of the Smart Patch system has been demonstrated in a real-world building application. However, the prototype system still has several options in improvements: 1) making the system capable of doing automated structure scanning and data distribution from the scan station around the sensor network. 2) The hardware system was proved capable of working with the piezoelectric transducers and temperature sensors, giving it the inherent capability for autonomous structural integrity monitoring. To miniaturize the system to be deployable in the field requires simplification of the system modules with the state of the art electronic fabrication technology, i.e. application specific integrated circuit design (ASIC) for Joint Monitoring Unit. 3) The sensor package is yet to be improved to be a self-contained system for in-situ deployment. The sensors will be integrated with printing circuits and miniaturized electronic circuit for processor, data acquisition devices, wireless communication and GPS functionalities.

6. FUTURE WORK

The future work to make this system development successful is targeted on the efforts with the following directions:

- The system requires 3D structure model graphic and visualization functionality feature that will be integrated in the next Smart Patch software release
- For further implementing prognosis of building structural health monitoring, the structural inventory information, such as structural characteristics, design codes, and other engineering factors need to be archived in inventory database for performance of prognostic process. This can be investigated and integrated to Smart Patch application.
- The system is potential to include the Life Cycle Cost Analysis for the long term management strategies.
- Acellent will collaborate with building owners or management associates for full scale validation.
- Acellent will collect feedbacks and recommendations from the end-users and creating transformational results to building management industries and emergency response sectors.

ACKNOWLEDGMENT

This research is supported by the Department of Homeland Security, Science and Technology Directorate, Small Business Innovation Research (SBIR) Program under Contract No. NBCHC070100.

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