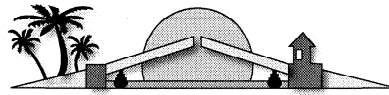


HEAVY MOVABLE STRUCTURES, INC.



NINTH BIENNIAL SYMPOSIUM
"Preserving Traditional Values with New Technologies"

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HEALTH MONITORING OF THE RETRACTABLE ROOF AT SAFECO FIELD

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INTRODUCTION

SAFECO Field (Figure 1), seating approximately 47,000 spectators, is home to the Seattle Mariners baseball team and contains a stadium club, restaurants, and state-of-the-art clubhouses. The stadium's retractable roof is an integral part of the design. The roof does not seal the facility, but acts more like a giant umbrella. This roof has been designed and constructed to both expose as many fans as possible to the outdoors when retracted and extend to protect fans and players from inclement weather in approximately 10 minutes.



Figure 1 - Aerial view of SAFECO Field

CTL was awarded the contract to design, install and maintain an autonomous monitoring system for the retractable roof at SAFECO Field. This customized instrumentation system will determine and remotely report the percent damping in the structure by monitoring the dynamic movement of the roof panels during large windstorms and earthquakes.

The results will be analyzed by Skilling Ward Magnusson Barkshire (the engineers for the roof design) and compared with the original baseline damping values to quickly pinpoint any degradation in the performance, further assuring the safety and entertainment of fans and players alike, while preserving the community's investment.

BACKGROUND

FACILITY DESIGN

In February 1996 the Public Facilities District selected NBBJ as the architectural firm to design the new ballpark. NBBJ Sports and Entertainment, a division of NBBJ, focuses exclusively on the design of sports facilities. Of the dozen or so other sports facilities, two of the more notable projects include Milwaukee's Miller Park and Seattle's KeyArena.

Design subcontractors include Skilling Ward Magnusson Barkshire (SWMB) as the structural engineers for the roof design, Weinstein Copeland Architects as the architects for urban planning, Flack + Kurtz Consulting Engineers as the engineers for mechanical, electrical and plumbing and Shannon & Wilson as the consultants for geotechnical and environmental issues.

The façade is designed with a scale and character similar to old Pioneer Square warehouses in the adjacent neighborhood. Steel was used in the stadium to help visually link the stadium's traditional design with that of the roof structure, as well as to evoke the nearby rail tracks and Port of Seattle's cranes. The mechanism that moves the roof is the same type that moves the waterfront cranes. The height and scale of the roof members are the same as the cranes. The green colored steel evokes the traditional style of old ballparks such as Fenway Park.

FACILITY CONSTRUCTION

Hunt-Kiewit formed a joint venture for the general contracting and construction management for this design-build project. Together, these two companies have combined experience building 22 stadiums, including other retractable roof stadiums and several domed stadiums. Huber, Hunt & Nichols, Inc. is a nationally recognized leader for stadium and long-span roof design and construction and has teamed with the ballpark architect NBBJ on twelve other projects including several sports facilities. Kiewit Construction Company consistently ranks among the 25 largest construction companies in the US with a branch office in Renton, WA. Kiewit has worked with Huber, Hunt and Nichols, Inc. on numerous large-scale construction projects.

It took just 27-1/2 months to build SAFECO Field at a cost of approximately \$517 million. The 19.5 acre site was former tidelands covered with fill, forming a soil consistency of oatmeal – not stable enough to build a sports stadium in a high seismic zone. The foundation required more than 1,400 pilings driven down to an average depth of 90 feet to connect with bedrock. The pilings were connected at the surface by reinforced concrete to form a stable foundation for the new ballpark.

The ballpark was built as seven separate buildings due to seismic requirements, so that the building could shift against itself without breaking during an earthquake. The separation of the bowl had its advantages in that work could be underway at the field level in one section while upper deck work could be performed in other areas. When one trade finished its work in one section, the next stage of work could begin in that section, allowing mechanical, electrical and plumbing work to follow quickly after concrete had been poured.

RETRACTABLE ROOF

The retractable roof consists of three self-supporting sections covering nearly 11 acres. The roof is unique in that when it opens, it moves almost completely off the bowl, leaving fans inside the benefit of a completely open-air park. When open, the arched panels nest over the railroad track just to the west of the park (Figure 2). Two smaller end panels tuck under the larger center panel, forming a grand arch similar to the old railroad stations found throughout Europe. When closed, the roof acts like an umbrella over the fans and the field to protect against rainy weather but preserving the open-air environment. Since the roof sits on legs mounted on wheeled mechanisms, the sides are open, providing views of the city and surrounding area even when closed.



Figure 2 - Roof in open position (nested)

The roof moves along on two sets of tracks using 128 wheels on travel truck assemblies driven by 96, 10-hp motors. The tracks are on top of runways at the north and south ends of the park (Figure 3). The travel trucks were built by Ederer's shop in Seattle just blocks from the ballpark then hoisted by cranes into place on the runways. The roof trusses were then built and placed onto the travel truck assemblies.



Figure 3 - Travel truck assemblies on top of elevated runways

The 655-foot span of the roof truss is larger than many bridges. The roof weighs over 11,000 tons, is 224-ft from the field to it's highest interior point and 269-ft to the highest exterior point of the roof truss. The roof can be opened or closed in approximately 10 minutes at a speed of about 60 feet per minute. The roof can support 80-90 psf or up to 7 feet of snow. The roof was designed to withstand and operate in sustained winds of up to 70 mph and have specially designed shock absorbers to protect the roof system in these high winds or an earthquake.

The roof trusses span the distance from the higher elevated runway on the south side to the lower runway on the north side (Figure 4). This span distance is 631 feet for roof panels 1 and 3 which are tucked inside roof panel 2 which spans 655 feet. The trusses on all three roof panels have fixed moment connections on the south side and pinned and dampened connections on the north side. This allows the roof to 'flex' in high winds or during seismic events without over-stressing truss components or carrying horizontal forces down to the travel truck or tracks on the runways.

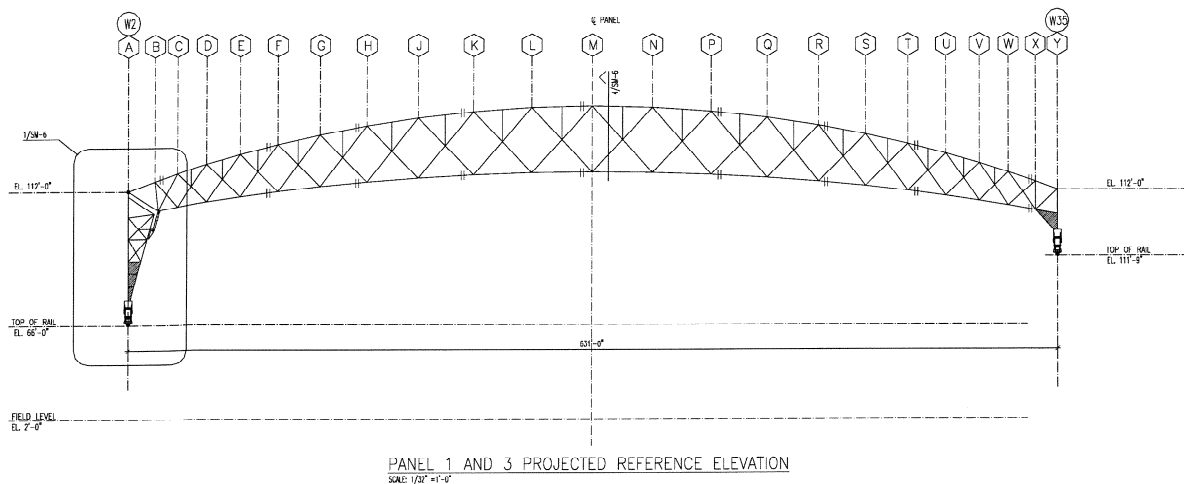


Figure 4 - Section view of Panel 1 and 3 roof truss

ROOF DAMPERS

Since the north side is pinned and free to move, the three retractable roof panels have a total of eight 800-kip viscous dampers mounted between the horizontal trusses and the down-turned north legs (Figure 5). These units act as large shock dissipaters to dampen lateral loads through the roof truss structure from wind and seismic events and minimize lateral loads transferred to the runway support structures. Without the use of these dampers, excessive vibrations/displacements could occur, causing damage to the roof panels and/or the drive mechanism. Therefore, the long-term performance of these dampers is essential for proper roof operation.



Figure 5 - Roof dampers on North side of truss

Because of the large size, high capacity and removal access of these dampers, long-term verification testing of these devices posed a problem. Without a seismic event or extremely high winds, the performance of the damper could not be verified. One of the options to assure proper operation of the dampers was to replace them one at a time each year with the spare in storage. Once removed, the damper could be sent out to a testing facility and the performance could be verified and documented. This unit would then become the spare for replacement of another damper the following year. This would mean that a damper would be in place for up to 8 years before performance could be verified.

Another option would be to continuously monitor the performance of these dampers to ambient wind conditions with the possibility of documenting performance during a seismic event. Since the dampers act as large shock absorbers, a force-displacement hysteresis could be created for each damper. This would require instrumenting each damper to measure actual displacement of the piston and the force required for that displacement. Since each damper would respond differently, the initial force-displacement signature for each damper would be needed to compare with later results. The flattening of the hysteresis would be an indication of a reduction in damping capabilities.

Skilling Ward Magnussen and Barkshire (SWMB-the engineers for the roof design) recommended the later option. Since they were recommending this option, they also realized the potential benefit of measuring wind speed/direction, seismic acceleration and roof panel movements. This concept was packaged as a 'Structural Health Monitoring Program for the Retractable Roof Panels at SAFECO Field.

STRUCTURAL HEALTH MONITORING SYSTEM

This state-of-the-art monitoring system uses a wireless local area network (LAN) to gather data from remotely positioned signal processing units (SPUs). The SPUs continuously monitor forces, displacements, accelerations of roof components and wind speed/direction at roof level and correlate these measurements under normal roof operation, high winds or seismic events. Remote access to the system is through modem, network or internet.

The system was installed in August/September of 2000 and placed in operation before the end of September, 2000.

SENSORS

Each of the eight dampers is instrumented to measure piston stroke displacement and force.

The displacement is measured using magneto resistive type displacement transducers with a stroke of ± 12 inches as shown in Figure 6. This type of sensor is robust and well suited for the extreme environment of Seattle.

The damping force is measured using strain gages spot-welded around the circumference of the damper strut leg as shown in Figure 7. The strain gages are wired together in a Wheatstone bridge configuration to increase sensitivity and output. This type of gage is installed completely encapsulated and is well suited for the extreme environment of Seattle.

The installation of these sensors was performed using a crane supported man basket.

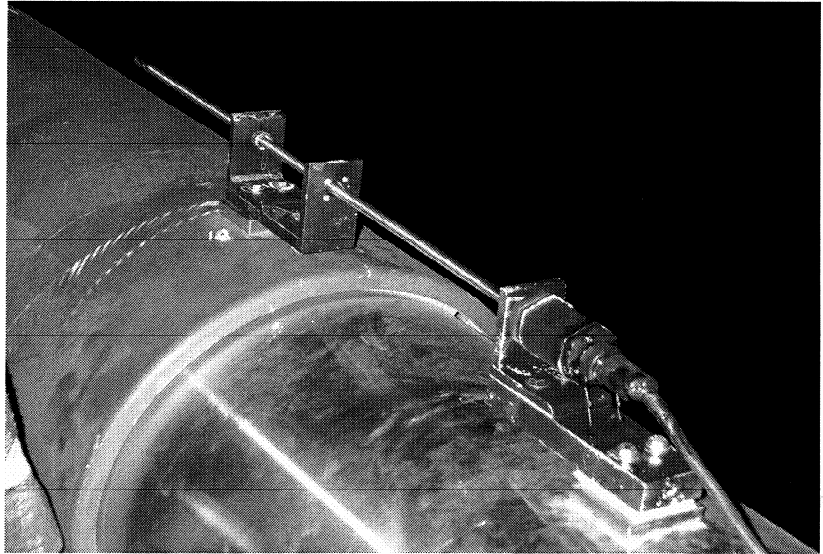


Figure 6 - Displacement transducer on damper piston



Figure 7 - Strain gages spot-welded on damper strut

Each of the three roof panels have a triaxil accelerometer (Figure 8) located at mid-span of the truss to measure roof vibration and displacement in three directions. In addition, a seismic triaxial accelerometer was installed in the foundation to record accelerations during a seismic event.

Wind speed and wind direction are measured using the previously installed anemometer sensors on the top of the roof.

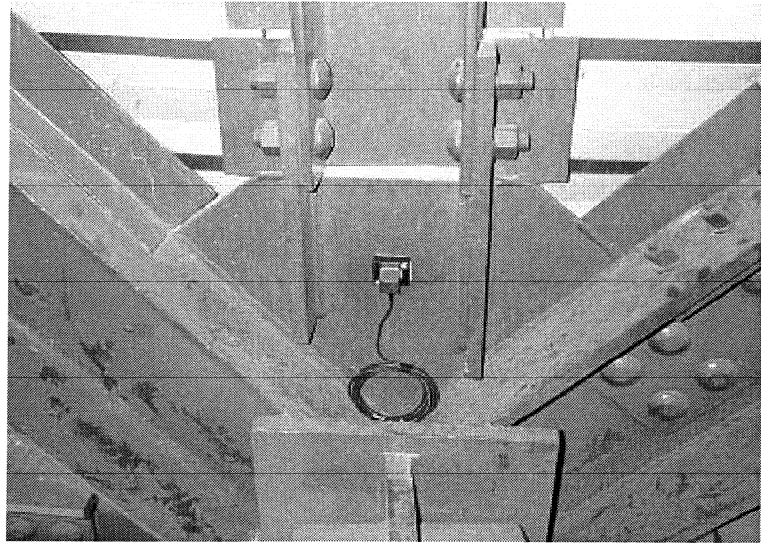


Figure 8 – Tri-axial accelerometer mounted on roof truss

SYSTEM COMPONENTS

A total of 28 sensors were installed on the retractable roof panels as shown in Figure 9. Since each of the three roof panels is instrumented with sensors and move relative to each other, hardwiring the sensors to one system would be difficult. Instead, each roof panel had its sensors connected to its own wireless data acquisition system or remote station (RS#). Lead wires from all sensors are routed along roof beams and girders to the respective remote stations housing the data acquisition system for each roof panel. Another data acquisition system was located in the retractable roof control room to monitor the seismic accelerometer and wind speed and wind direction sensors. In that same room, a central computer was located to control data communication and archive data from the four remote stations.

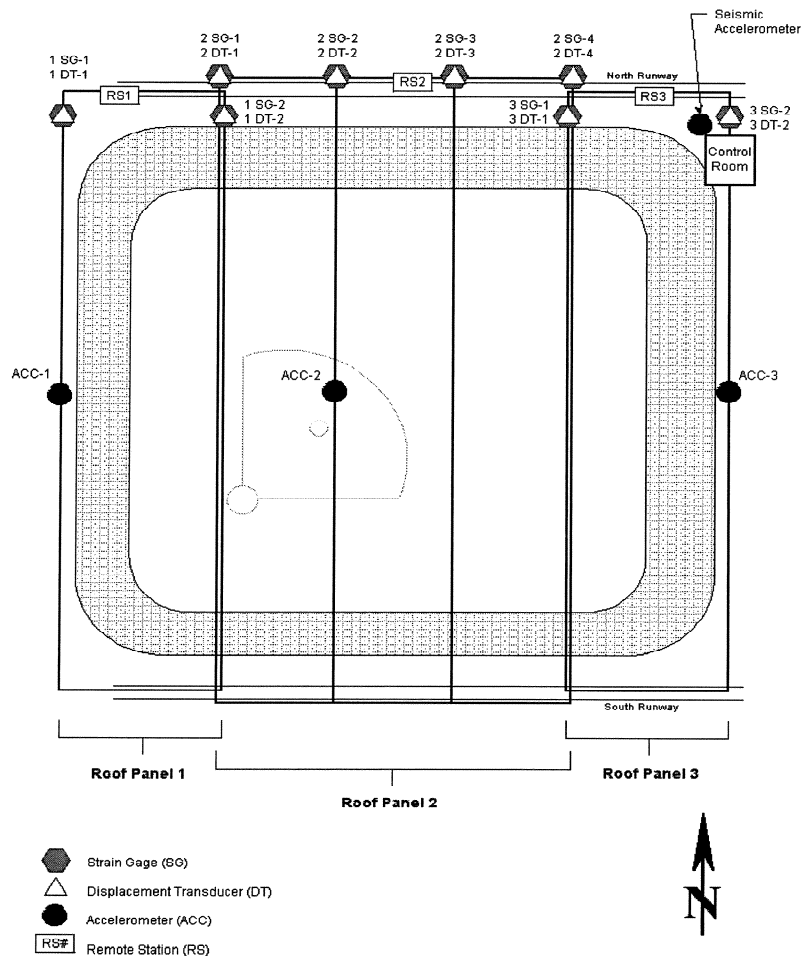


Figure 9 - Sensor and System locations

The system schematic is shown in Figure 10. For remote stations RS-1, RS-2, and RS-3 a NEMA enclosure is used to house this system and provide a protective operating environment for the remote station components. A stainless steel enclosure is non-corrosive and provides protection from Electrical Magnetic Forces (EMF). A fourth data acquisition system is hardwired to the central computer.

Each remote station and the central computer required the system components to be physically secured and a minimum of 5-hour battery backup in the event of lost power in an earthquake. This would allow the system to keep functioning and still allow for remote access for data retrieval.

SYSTEM OPERATION

The operation of this system is intended to provide continuous data gathering from the sensors in each of four locations. The three remote stations run individual software programs and send the data through a wireless LAN to the Central Computer while the fourth station is hardwired to the LAN in the Roof Control Room. The data from these four stations are streamed directly to the

Computer's hard drive and continuously updated on the 17" monitor in real time in a strip chart mode. At the end of a 24 hour period, the computer sends out commands to stop the four data acquisition units, close the respective data files, resynchronize their clocks and start the systems up again. All this takes place in about 1 second.

The sampling rate is currently set at approximately 50 readings/sec/channel. Data is stored in 24-hour blocks with only the most current 10 days of data residing on the Central Computer. All acquired data is automatically time and date stamped. This allows for ease in data management and correlation of data with specific timed events such as roof opening and closing, high winds or seismic events.

A software routine is also run in the background at the end of the day to automatically open the four files from one day and merge these into one large data file for each day and post the data in graphical form to an ftp site. Each application will graphically display the waveform on the screen as shown in Figure 11.

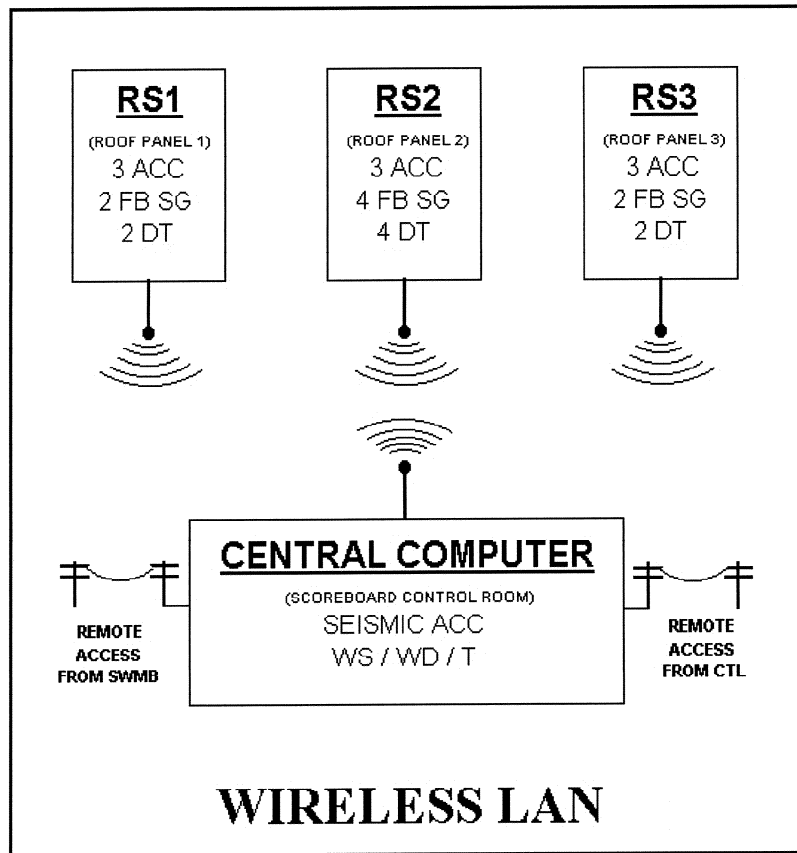


Figure 10 - System schematic

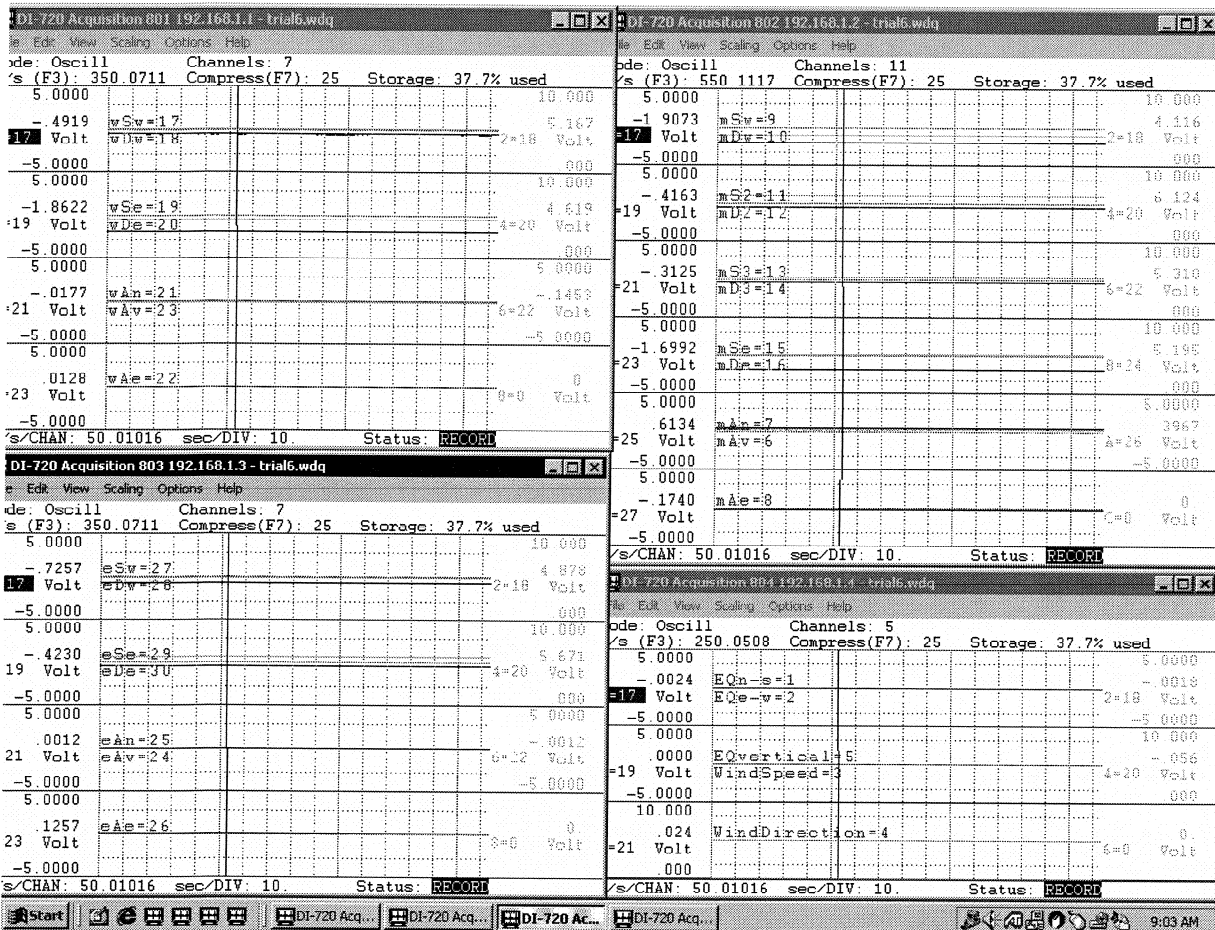


Figure 11 - Central computer display showing four data acquisition system windows open and running simultaneously

REMOTE ACCESS

Remote access to the Central Computer (thereby the system) can be through relatively low-speed dial-up modem or high-speed network connections. In addition, data from the previous 24-hour time period is automatically posted onto a ftp site.

The system can be accessed remotely through a modem dial-up connection using pcAnywhere software. Once logged onto the Central Computer, the remote user emulates the host (remote user's keyboard and screen are as if the user is sitting in front of the Central Computer) – only slower. This relatively slow connection allows for remote interrogation of the system, periodic system checks and as a through link to the system DAS/communication firmware using telnet software residing on the Central Computer.

The system can also be accessed through network connection using pcAnywhere software. This is a much higher speed connection and is remotely available only when connected to a network and running psAnywhere software.

STRUCTURAL RESPONSE FROM EARTHQUAKE

The Nisqually Earthquake put the system and roof structure to the test on February 28th, 2001. This seismic event occurred at 10:54 am and was the strongest earthquake to hit the Pacific Northwest in 50 years. Its epicenter was 11 miles northwest of Olympia, WA and had a magnitude of 6.8. The system performed as designed. The information obtained from the measured data indicated proper functioning of the roof dampers and acceptable movements and response of the roof panels to this seismic event.

Figures 12 through 15 show actual data from the earthquake as recorded by the system.

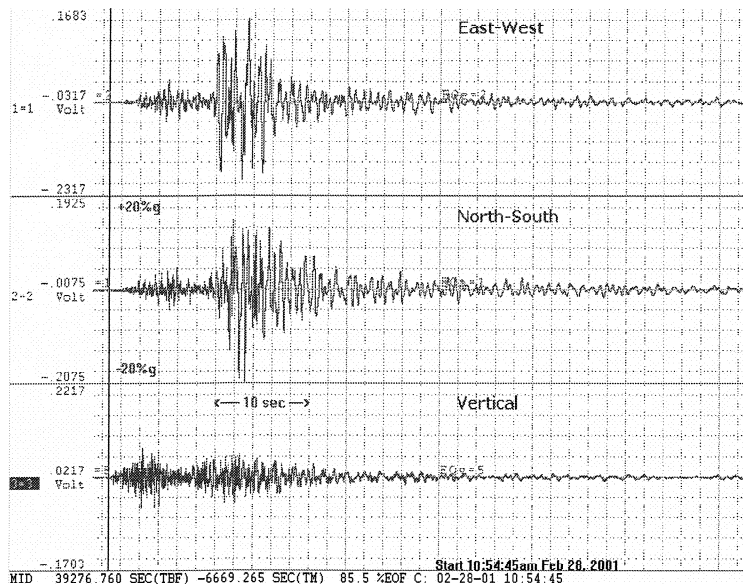


Figure 12 – Ground accelerations measured from the on-site seismic accelerometer attached to the foundation

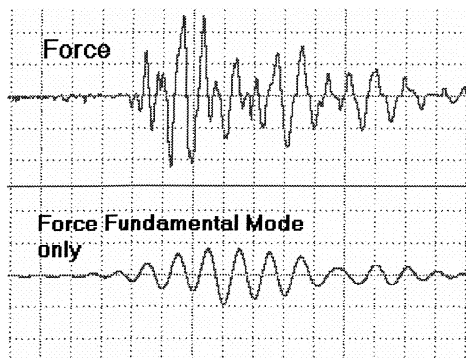


Figure 13 - Force Fundamental Mode only obtained from force measurement

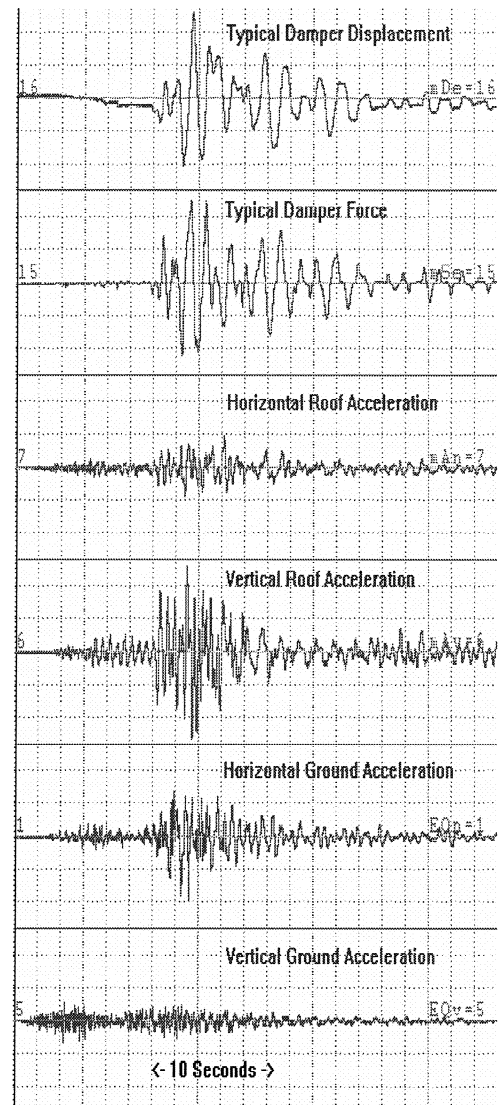


Figure 14 – Measured response from various sensors

Note in Figure 15 the “fat” hysteresis. This indicates the work performed by the damper. This also provides a signature for this particular damper and would be compared with plots of subsequent response of this damper to high winds or other seismic events. Even normal roof operation can activate the dampers.

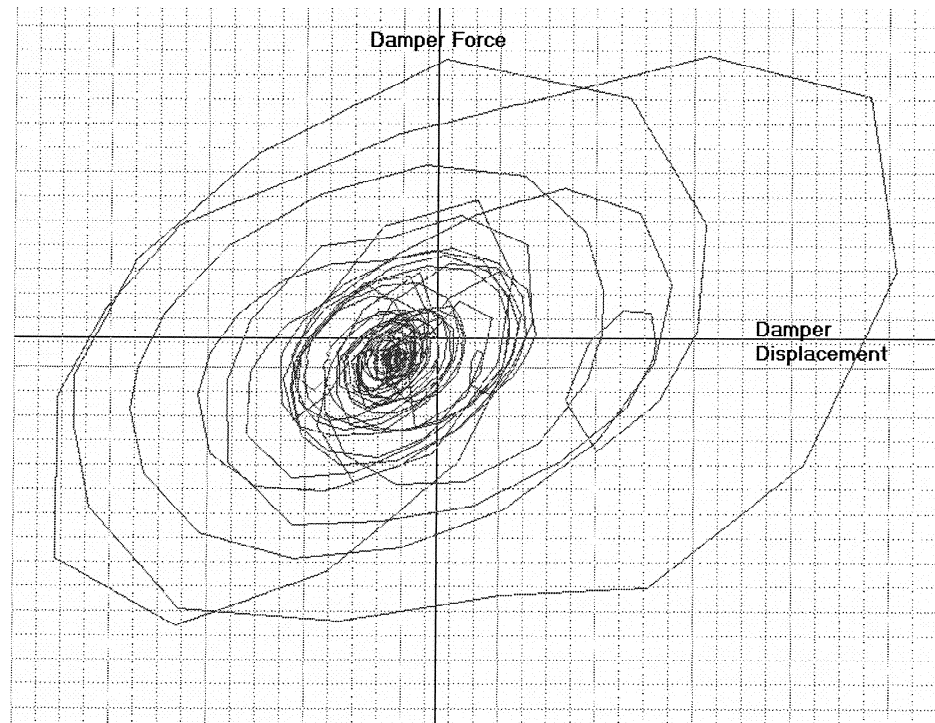


Figure 15 - Typical Force-Displacement hysteresis

SUMMARY

The proper operation of the roof dampers is essential to the health of the roof structure, drive components and supporting track way over the life of the structure as a result of expected high winds and possible seismic events. The structural health monitoring system for the retractable roof at SAFECO Field was installed as an economical solution to evaluate the long-term performance of the roof damping system. The results of the data obtained during the February 28, 2001 Nisqually earthquake proved the system worked as designed, provided an economical solution to expected high maintenance costs and saved the owners tens of thousands of dollars in inspection/evaluation costs after a major potential catastrophic event.