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Progressive Collapse Analysis of an Existing Building

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This research study investigated a structure's potential to fail due to progressive collapse. Progressive collapse in a structure occurs when major structural load carrying members are removed suddenly, and the remaining structural elements cannot support the weight of the building and fail. This failure usually occurs in a domino effect and leads to a progressive collapse failure in the structure. This experiment involved testing of a steel building scheduled for demolition in Northbrook, Illinois. The demolition team tore out four selected columns from the building to simulate the sudden column removal that leads to progressive collapse. The author instrumented the beams and columns in the building, managed the testing and analyzed the recorded data. The strain values recorded in the field were compared with the results from a computer model of the building. The percent error between the calculated and measured strains in a selected column was 21%. The computer analysis conducted in this research was based on linear material properties. The ultimate goal of this ongoing progressive collapse research on real buildings was to develop better building evaluation and design guidelines for structural engineers to use to prevent progressive collapse in new and existing buildings. Future progressive collapse research recommendations are also presented.

Introduction

The progressive collapse of building structures is initiated when one or more vertical load carrying members, typically columns, is removed. Once a column is removed due to a vehicle impact, fire, earthquake or other man-made or natural hazard, the building's weight (gravity load) transfers to neighboring columns in the structure. If these columns are not properly designed to resist and redistribute the additional gravity load, that part of the structure fails. The vertical load carrying elements of the structure continue to fail until the additional loading is stabilized. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact.

This research began with the evaluation of the General Services Administration (GSA) Progressive Collapse Analysis and Design Guidelines (2003). The GSA guidelines provided general formulas and conditions that determined which members of a structure were susceptible to progressive collapse. Specifically, the demand-capacity-ratio (DCR) was used by the GSA guidelines to determine if individual members would fail, leading to progressive collapse. This research analyzed and investigated the progressive collapse of an existing building using the 2003 GSA guidelines. The structure was a three story building located in Northbrook, Illinois. Built in 1968, the structure had reinforced concrete (RC) members in the basement, concrete slabs for the flooring and was composed of steel framing on the first and second floors. The sixth edition of the AISC Steel Construction

About the Author

Kevin Giriunas is a first year civil engineering graduate student at The Ohio State University. His focus is on structural engineering and he has an expected graduation date of June of 2011. Working under advisor Halil Sezen, his Masters Thesis will involve developing a structural guideline for using shipping containers as housing for emergency and military applications. He is getting married in May of 2011 and hopes to work for a sustainable engineering consultant/firm that incorporates structural engineering with "green" design.

Manual (1963) was used to design the structure and the building was scheduled for demolition in early August, 2008.

Following a predetermined testing procedure, developed following the GSA guidelines, the demolition team removed four columns from the existing structure. In order to measure the strains in various columns and beams, the structure was instrumented with strain gauges prior to the column removals. As each column was removed, the strain gauges captured the data that was later analyzed and compared with the analysis results from the computer program SAP2000 (2008).

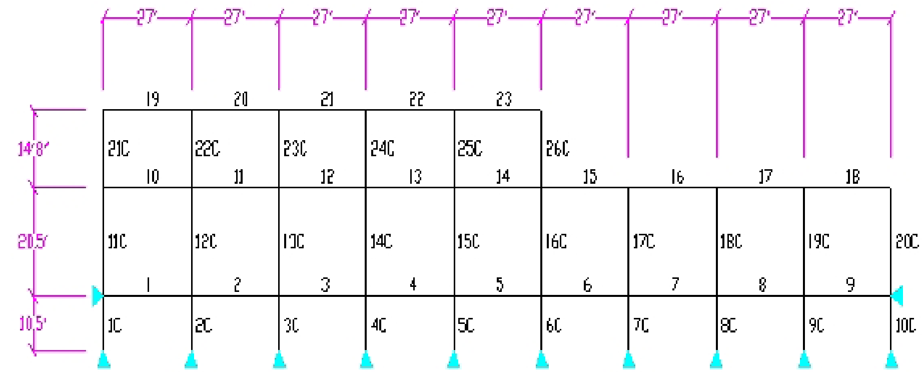

Figure 1. Elevation of North End Frame of the Building.

The Structural Analysis Program (SAP2000) is a powerful computer program used to design and analyze various structures. The program analyzes two dimensional linear static models to three dimensional nonlinear dynamic models. This study involved linear elastic static analysis of the structure. The data obtained from the strain gauges on the actual structure during the demolition was compared to the analysis results of the linear static model in SAP2000.

The strain measured from the strain gauges in the field was used to understand the response of the structure during and after column removals. The load distributions, change in strains and bending moments generated from each column removal were calculated from the measured strain values collected in the field. The load distributions, change in strains and bending moments generated from each column removal were also calculated and compared in the SAP2000 computer simulation. This research study analyzed the data collected in the field and compared it to the SAP2000 simulation results to verify the GSA guidelines.

Experimental Research

Description of Building

The Bankers Life and Casualty Company insurance building, located in Northbrook, IL, was constructed in 1968 following the 6th edition of AISC Steel Construction Manual (1967) design code. The basement and first story were 10 ft-6 in. and 20 ft-6 in. in height (Figure 1). The heights of the lower and high points of the second story were 14 ft-8 in. and 15 ft-2 in., respectively. The building had nine bays spanning 27 ft wide in the longitudinal direction, and 8 bays spanning 23 ft-6 in. in the transverse direction (Figure 2). Table 1 shows the beam and column designation of the Bankers Life and Casualty Company building.

Experiment Information

The experiment involved recording the strain on various structural members as four columns were removed from the north side of the building (Figure 3). The Environmental Cleansing Corporation was hired to demolish the Bankers Life and Casualty Company insurance building. They agreed to help with the study, tearing out the four columns as specified in this research using GSA (2003) as a guideline.

Prior to removing the columns, the demolition team tore down the second floor near the northwest corner of the structure due to a miscommunication between the owner and the demolition team. As a result, all of the building materials remained on the second floor concrete slab. The joists, bridging joists, roofing, bricks, tie rods and concrete masonry units (CMU) created a rubble mass on the second floor slab. This rubble spanned the area of four bays east from the northwest corner and approximately two bays south, resulting in a slightly different loading scenario for the four columns nearest the northwest corner. Figure 4 shows the rubble mass at the north side of the building.

Experiment Procedure

The demolition team first exposed the columns and beams by removing the exterior brick wall. The surface of the columns and beams were then grinded down to remove all paint and debris. Next, a degreaser, conditioner and neutralizer were applied to the clean surface before attaching the strain gauges using an adhesive. The strain gauges were covered with a strain gauge shield to protect against debris. A total of nine strain gauges were used in the experiment, eight were attached on the columns and one was attached to a beam (Figure 5).

The strain gauges were attached to a portable data acquisition scanner system and laptop. During the column removal process, the computer measurement scanner and laptop recorded all nine strain gauge readings simultaneously.

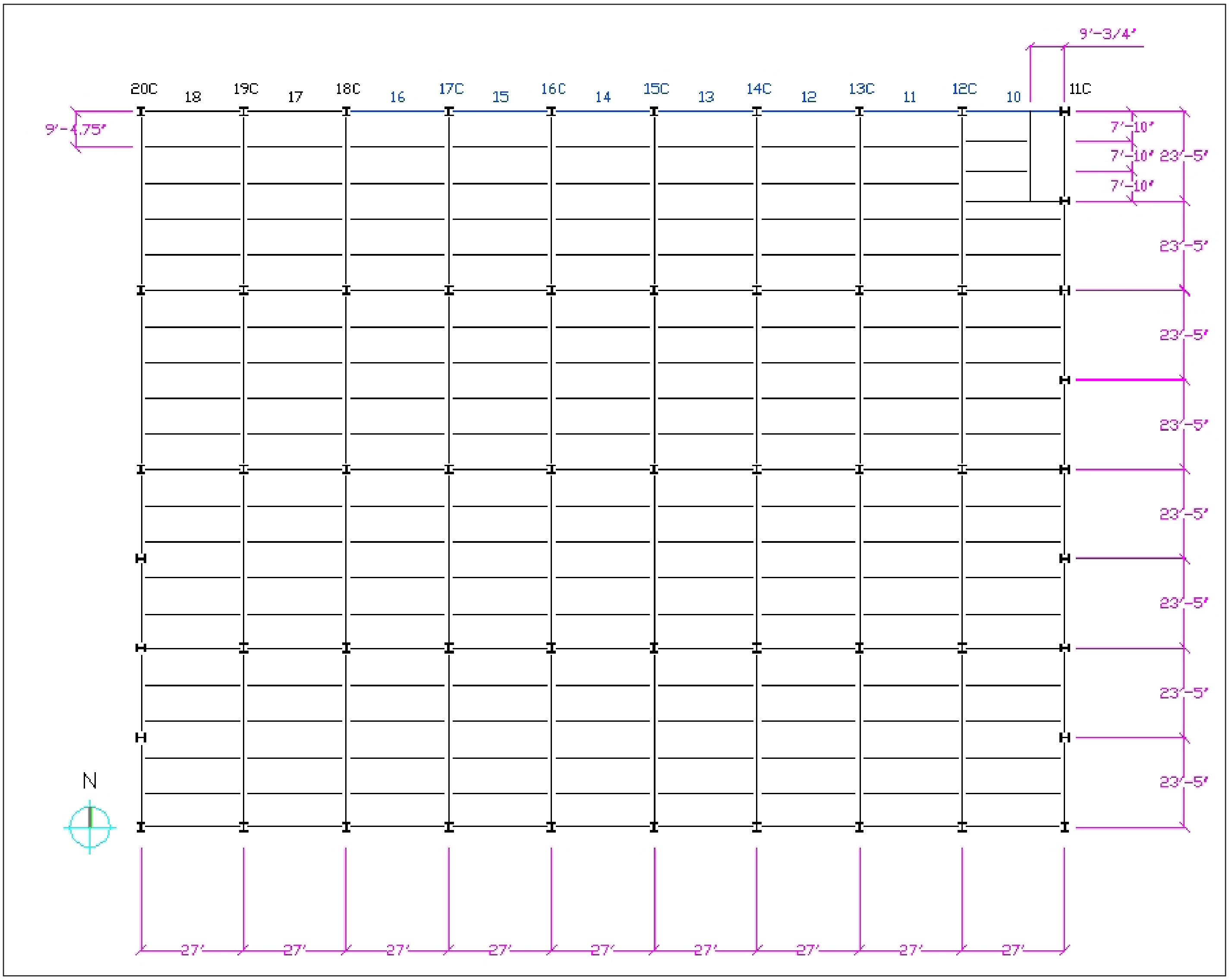

Figure 2. Dimensions for the Second Floor of the Bankers Life and Casualty Company Building and Experiment Location is Highlighted in Blue.

Table 1. Beam and Column Designation of the Building Corresponding with Figure 1.

Beam Number	Beam Type	Column Number	Column Type
1	RC Flat Slab	1C	RC
2	RC Flat Slab	2C	RC
3	RC Flat Slab	3C	RC
4	RC Flat Slab	4C	RC
5	RC Flat Slab	5C	RC
6	RC Flat Slab	6C	RC
7	RC Flat Slab	7C	RC
8	RC Flat Slab	8C	RC
9	RC Flat Slab	9C	RC
10	24 I 79.9	10C	RC
11	21 WF 62	11C	10 WF 49
12	21 WF 62	12C	10 WF 72
13	21 WF 62	13C	10 WF 72
14	21 WF 62	14C	10 WF 72
15	21 WF 62	15C	10 WF 72
16	21 WF 62	16C	10 WF 72
17	21 WF 62	17C	10 WF 72
18	21 WF 62	18C	10 WF 72
19	18 WF 45	19C	10 WF 72
20	18 WF 45	20C	10 WF 72
21	18 WF 45	21C	8 WF 31
22	18 WF 45	22C	8 WF 31
23	18 WF 45	23C	8 WF 31
		24C	8 WF 31
		25C	8 WF 31
		26C	8 WF 31

The strain values were recorded every tenth of a second during the column removal. Figure 11 shows the strain recorded in the field from a single strain gauge during each column torching and removal.

During the column removal process, each column was weakened by a blow torch prior to its removal for safety reasons. During the torching process, the demolition team melt nearly through each column's cross section at two points above the strain gauges. The distance between the torched lines on each column was approximately two

Figure 3. The Circled Columns on the North Side of the Building were Removed During the Experiment.

Figure 4. The Rubble Mass is Circled on the North Side of the Bankers Life and Casualty Company Building.

to three feet. The demolition team then melted a hole in the northern facing flange of each column between the torched lines. A chain was then attached to the hole and the column was pulled out by a large backhoe. Figure 6 shows the column torching and removal order, Figure 7 displays the computer station set up at the demolition site, Figure 8 shows Column 16C being torched, Figure 9 shows a torched column with a chain attached and Figure 10 shows Column 11C being removed.

Analytical Research

GSA Guidelines

The GSA Progressive Collapse Analysis and Design Guidelines (2003) define analysis procedures to evaluate the vulnerability of a structure against progressive collapse. When analyzing the structure for progressive collapse potential, GSA (2003) recommends a general loading factor to be used for every structural member in the building being tested. GSA (2003) factors the loading conditions using Equation 1:

$$Load = 2.0\ [Dead\ Load + 0.25\ (Live\ Load) \qquad (1)$$

Equation 1 is used for all loads acting on the structure and increases the loading condition to account for irregularities in the structure. This equation presents the worst-case scenario for the structure being tested for progressive collapse potential.

When vertical members are instantaneously removed, GSA (2003) uses demand-capacity ratios (DCR) to analyze which structural members will exceed their loading capacity and lead to progressive collapse. Using the linear elastic static analysis, the DCR values are found using Equation 2:

$$DCR = M_{max} / M_p \qquad (2)$$

where Mmax equals the moment demand calculated using linear elastic static analysis from SAP2000 and Mp equals the ultimate moment capacity (plastic moment) that can be calculated for each structural member. Using these two values, the DCR value for each structural member of the building was calculated. The DCR values calculated from Equation 2 could not exceed the DCR limits [determined

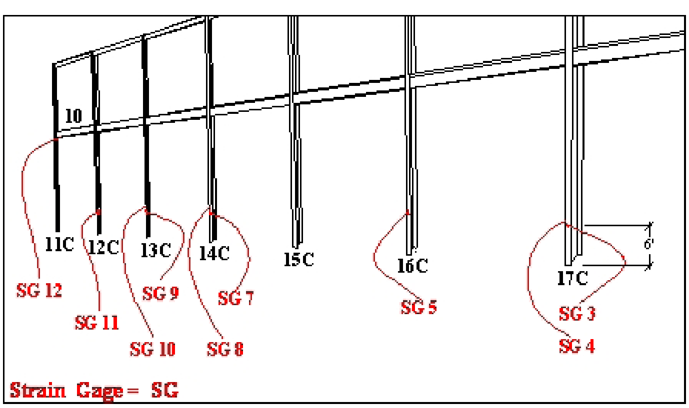

Figure 5. Strain Gauge Placement with Columns and Beam Labeled on North Side of Building.

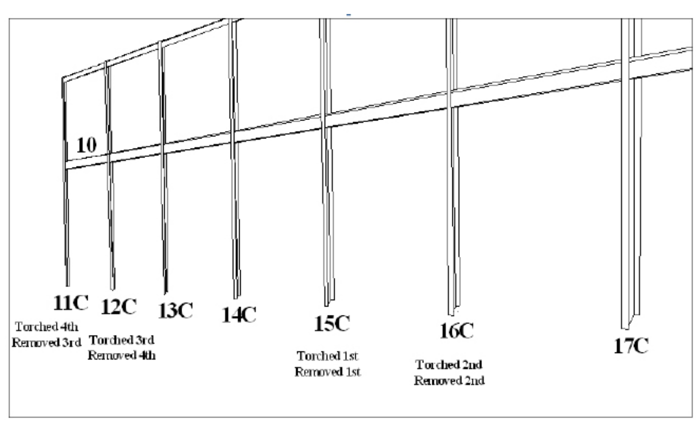

Figure 6. Order of Column Torching and Removal on North Side of Building.

Figure 7. Computer Station and Data Acquisition System.

Figure 8. Column 16C Being Torched.

from GSA (2003)] presented in Table 2.

SAP2000 Analysis

The structural analysis computer program, SAP2000, was used to analyze the Bankers Life and Casualty Company insurance building. A linear elastic static analysis was done on the two dimensional exterior frame located on the north side of the building, which took into account the effect of immediate surrounding structural members. SAP2000 analyzed the loading conditions caused by the structure's weight, and Equation 1 was used for the loading conditions. Therefore, all dead loads were multiplied by a factor of two.

The same procedure for the field experiment was implemented in the SAP2000 analysis and all the structural properties of the members were inserted into the computer model. The columns were removed in SAP2000 in the same order they were torched in the field. The computer model of the structure in SAP2000 analyzed the original building conditions and each subsequent column removal.

The SAP2000 computer simulation was performed after each column was removed on the model and the results were analyzed. Figures 12 through 17 show the SAP2000 bending moment diagrams and demand-capacity ratio values for the two dimensional exterior frame on the north side of the structure. The DCR values in red in Figures 12 through 17 exceeded the specified DCR limits shown in Table 1.

Column 12C was torched third and removed last in the field, but was removed third in SAP2000. This removal was done deliberately, because the strains had the largest readings when the columns were torched and barely reacted and changed when the columns were removed. For this experiment, the column torching order in the field was the SAP2000 column removal order.

Figure 9. Torched Column Ready to be Pulled Out.

The SAP2000 study conducted showed eight columns and seven beams exceeded their respected DCR limits when all four columns were removed (Figure 16). These members were deemed susceptible to progressive collapse. Some of the DCR values for the members exceeded the specified DCR limit by a factor of eight. These high DCR values could partially be due to the inaccuracy in dead and live load predictions. Approximately half of the second

Figure 10. Torched Section of Column 11C Being Removed.

Table 2. Required DCR Limits for the Beams and Columns of the Structure.

Beam	DCR value
24 I 79.9	2.25
21 WF 62	3
18 WF 45	3
Column	**DCR value**
10 WF 49	1.9
10 WF 72	2
10 WF 77	3
8 WF 31	1.8

floor was collapsed by the demolition team (Figure 4) prior to the first column removal; the GSA guidelines required all dead loads be multiplied by a factor of two (Equation 1). Also, the structure could not redistribute the gravity loads as easily because it was a two-story structure, half of the second story was collapsed and large spans were present between columns. A taller structure probably would be able to distribute gravity loads to more members and would generate smaller DCR values as found in Sezen and Song (2008).

The strain (ε) for Strain Gauge 7 on Column 14C was compared with the generated SAP2000 ε values (Figure 17). Strain Gauge 7 was selected for this experimental study because it was believed to have recorded the most consistent and accurate data in the field. Figure 17 shows that the strain values recorded in the field from Strain Gauge 7 had an average 21% error between the field and SAP2000 results. These values were very close considering all the possibilities for error. The exact time of each column torching and removal was not recorded, the exact locations of strain gauges were not recorded and the demolition atmosphere could have caused recording discrepancies.

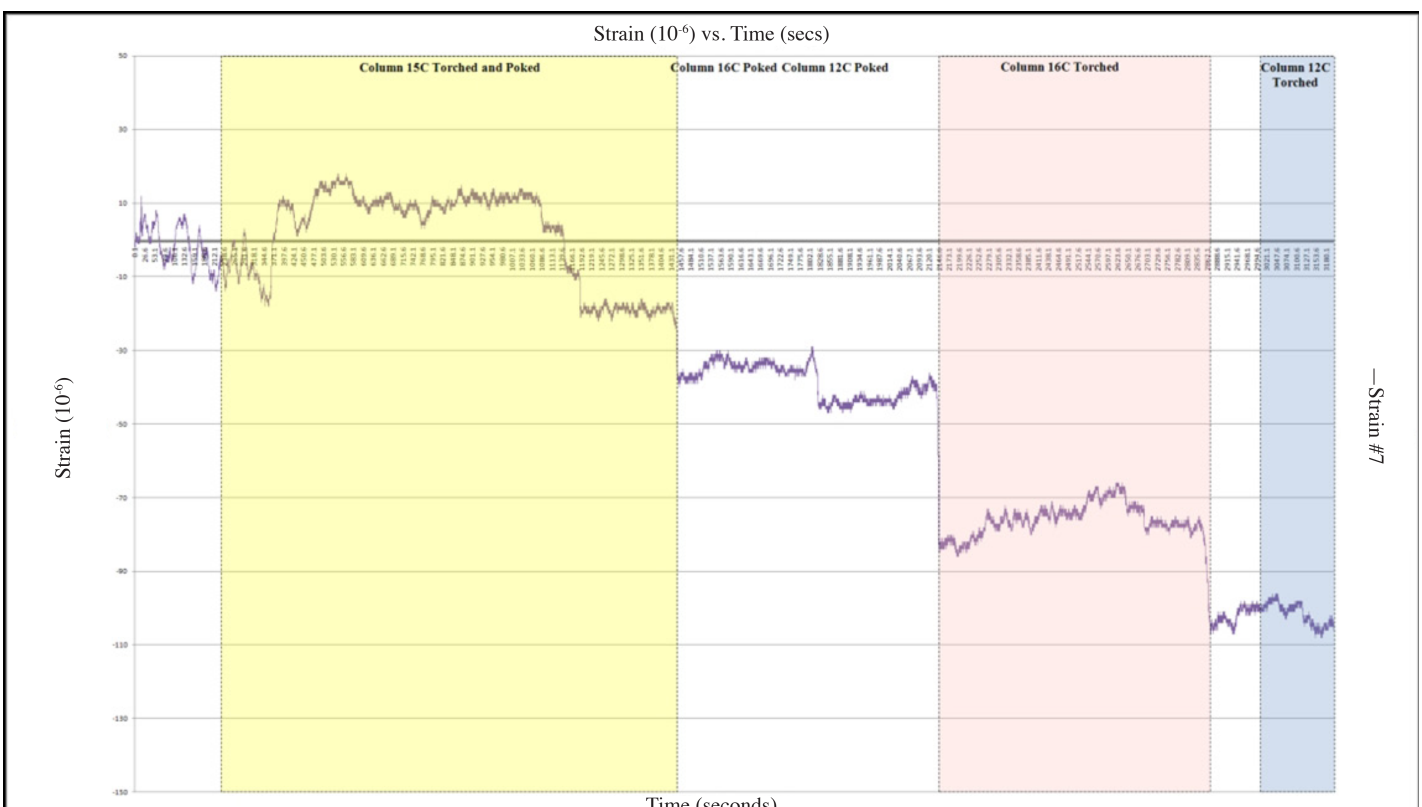

Figure 11. Strain versus Time Chart for Strain Gauge 7: Measurements during Torching (Time: 0-3200 seconds).

Future Experiments

Strain Gauge Placement

Strain gauges must be placed near the tops of columns at points A and C (Figure 18). It is expected that the maximum moment will occur at the top of the column both before and after the removal of neighboring column(s). The axial load will be constant over the length of the column. Strain gauges A and C should be sufficient to determine the strain distribution at the top of the column, and the change in loading (ΔP) and change in moment (ΔM) values acting on the column can be determined.

A strain gauge placed approximately one-third the length of the column from the bottom at point B (Figure 18) is predicted to record the strain from the axial load only. The ΔP can be calculated because ΔM is theoretically close to zero. This ΔP value can be checked with the ΔP calculated from the strain gauge readings near the top of the column at points A and C shown in Figure 18, and should be similar in value.

At least, a single strain gauge should be placed near the end of the beam at either point A or C (Figure 19). Since beams are rarely subjected to an axial load, placement of a strain gauge at point B in Figure 19 is probably not necessary. Theoretically, the strains due to bending moments will be the same at points A and C in Figure 19. Using the strains recorded at point A or C, the ΔM can be determined since ΔP is approximately zero. In order to capture the stress change at beam ends, at least two strain gauges are necessary, one on the top flange and another on the bottom flange at the ends of beams jointed above a removed column.

In this study, a general procedure was developed for removal of first story columns from a regular frame building. The procedure illustrated in Figure 20 demonstrates the order for which columns should be removed. For safety reasons, the columns all have to be torched first, and the columns should be removed in the same order. Following the procedure previously described, the column circled 6th should be torched first. Prior to torching, the 2nd floor has to be supported near the column circled 6th (Figure 20). Steel supports being developed will support the weight of the structure above the interior column circled 6th, and a jacking system will hold the supports in place. The interior column is to be torched and removed while the support mechanism supports the weight of the structure above the column. The jacking system will be disengaged once the interior column is to be removed.

The interior column circled 6th will be considered removed once the jacking system is disengaged. The columns circled 7th and 8th are optional to be torched and removed. Also, it may not be possible to remove columns circled 5th and 8th if the left side of the building is not accessible for testing.

Ideally, each column needs to be removed immediately after it is torched. This is almost impossible to do for safety reasons. Instead of using the torching method, a controlled blast can be the best method for removal of columns. Several critical columns would be attached with explosives, and all exterior and interior columns could be removed in a set order until collapse occurs. Controlled explosives would eliminate the need for the steel support jacking system, and create a more realistic progressive collapse scenario.

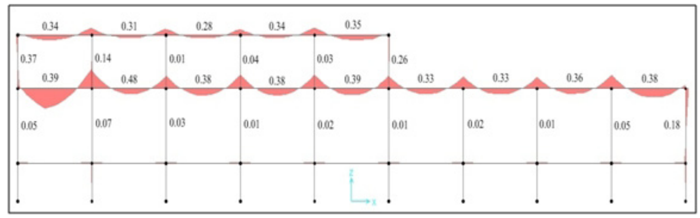

Figure 12. SAP2000 Model of Original Intact Building with DCR Values.

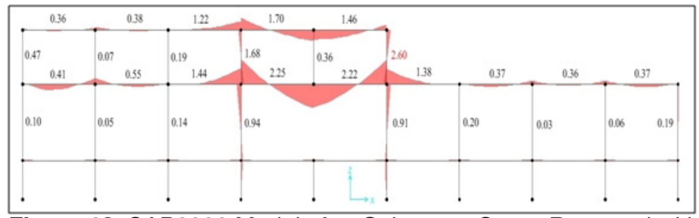

Figure 13. SAP2000 Model after Column 15C was Removed with DCR Values.

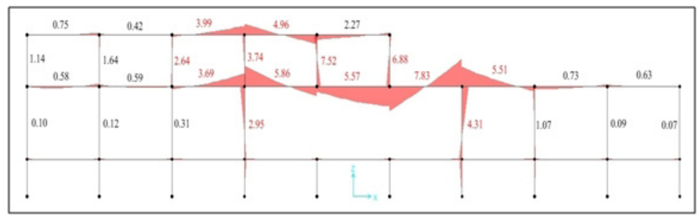

Figure 14. SAP2000 Model after Columns 15C and 16C were Removed with DCR Values.

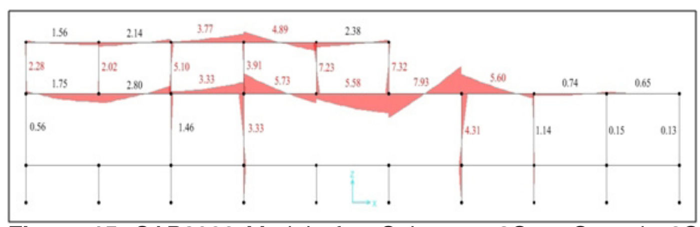

Figure 15. SAP2000 Model after Columns 12C, 15C, and 16C were Removed with DCR Values.

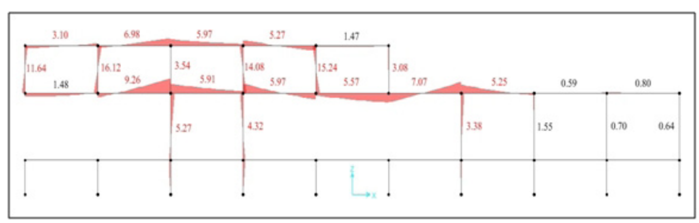

Figure 16. SAP2000 Model after Columns 11C, 12C, 15C, and 16C were Removed with DCR Values.

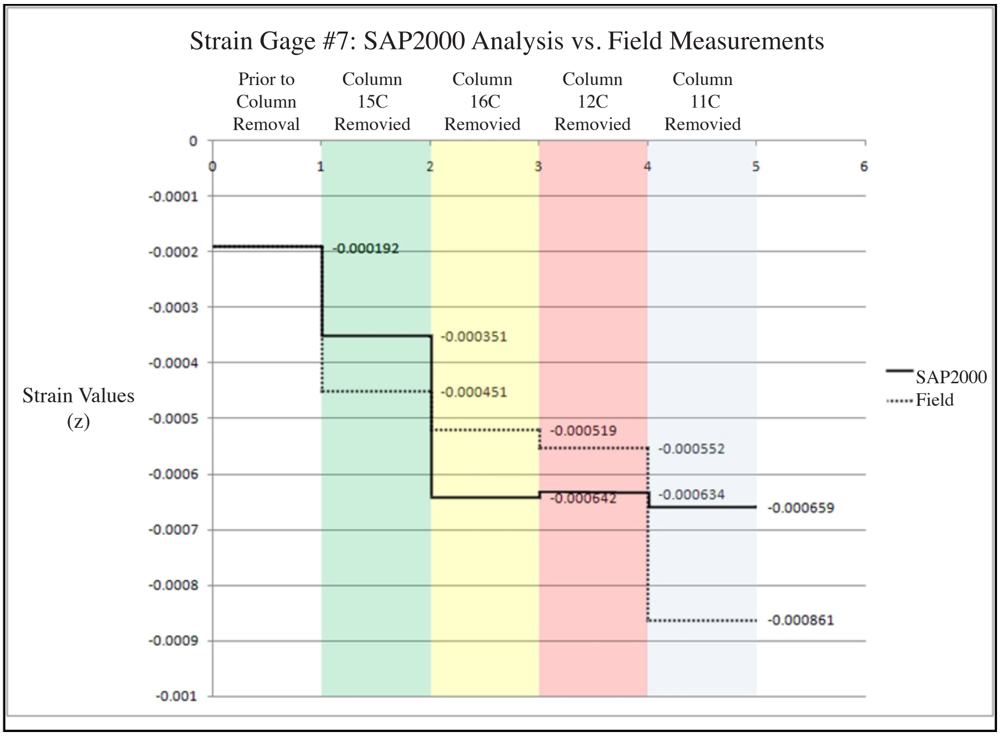

Figure 17. SAP2000 and Field Strain Values Shown for Strain Gauge 7 (21% Error between SAP2000 Results and Actual Measurements).

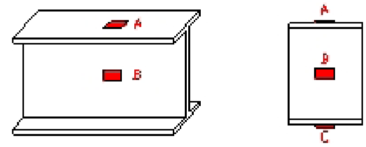

Figure 18. Strain Gauge Instrumentation on a Column.

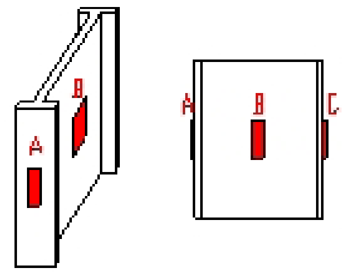

Figure 19. Strain Gauge Instrumentation on a Beam.

Conclusions

The building itself was unique because some of the second floor was collapsed prior to initiation of the experiment. Future structures should be fully intact and not damaged. The DCR values and some SAP2000 analysis results were excessively high due to the unique properties of the structure, inaccurate data recording and demolition site inconsistencies. However, a great deal was learned and investigated from this research study.

Future progressive collapse experiments will be more informative and accurate. A more in depth SAP2000 analysis will be developed for future research that will analyze every member on the structure near the removed columns. The SAP2000 analysis for this experiment was similar to some of the strain gauge recordings, and Strain Gauge 7 had an average 21% error from the SAP2000 analysis. The DCR values deemed the structure to be at high risk for progressive collapse when all four columns were removed, while the field recorded strains did not come close to failure. It should be noted that DCR values were calculated from linear elastic static analysis, as recommended by GSA (2003). A more accurate numerical simulation should include the material nonlinearity, three-dimensional and dynamic effects which are the subject of future research.

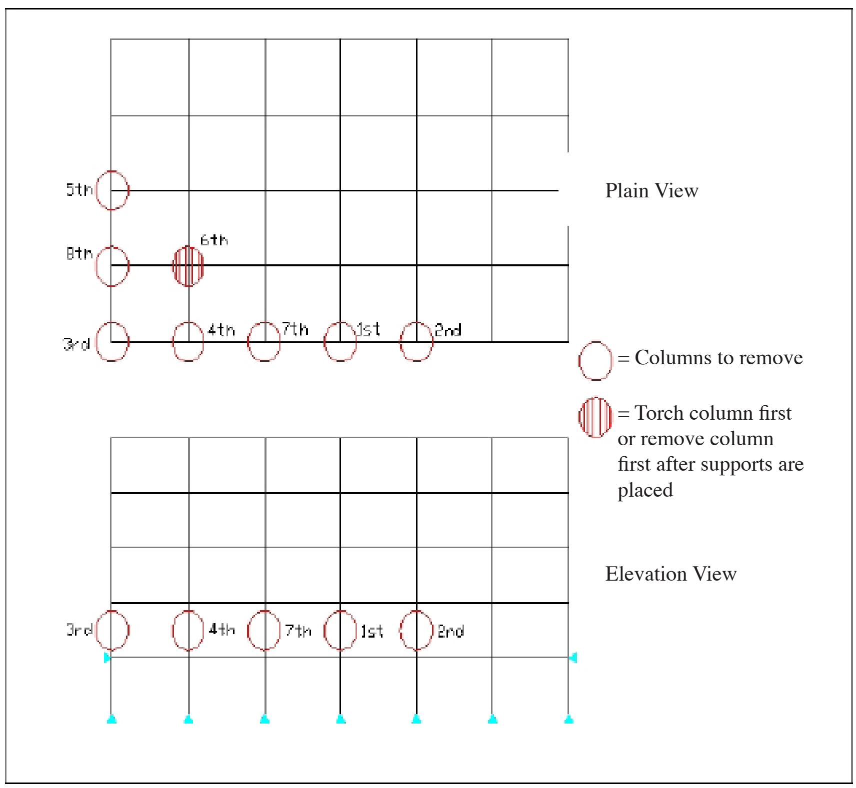

Figure 20. Suggested Order of Column Removal for the First Floor.

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