Influence of Boundary Conditions on Building Behavior

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Abstract:

When architectural engineering students graduate and enter the workforce they will be faced with analyzing and designing a variety of structural systems. Great care is often taken in accurately modeling the structure until it comes to the boundary conditions at the base of the building. Most students are exposed to fixed boundary conditions, pinned boundary conditions and roller boundary conditions in their undergraduate courses. These idealized boundary conditions simplify the analysis, however, choosing which condition is appropriate for connections in an actual building is not always clear. In addition, boundary conditions can have a large influence on the predicted building performance and associated design. Engineers are challenged with accurately modeling buildings including the boundary conditions, and therefore, facing this challenge in their undergraduate studies is important for students so that they can make informed decisions as engineers.

Integrating experiments into courses uniquely exposes students to the challenges they will face as practicing engineers. In a senior level design and analysis course students were assigned the task of determining the appropriate boundary conditions for a two-story steel moment frame with columns bolted to a concrete floor. The students predicted the steel frame response by computational models and hand calculations. They completed the hand calculations first to provide a baseline for the computational models. After predicting the steel frame response the students conducted dynamic experiments to measure the response of the frame to serve as a comparison for their predictions. This laboratory experience gave students a healthy skepticism for analysis results that are not validated by hand calculations and encouraged students to consider how design details affect the boundary conditions and overall structure behavior.

Introduction:

Idealized boundary conditions are convenient and often appropriate for structural analysis. Undergraduate engineering students are typically introduced to the following idealized boundary conditions: fixed boundary conditions restraining rotation and displacement, pinned boundary conditions restraining displacement while allowing rotation and roller boundary conditions, restraining displacement in one direction while allowing displacement in the perpendicular directions and allowing rotation. Most steel frame buildings are bolted to a concrete foundation. This often results in a boundary condition that lies somewhere between the idealized cases of fixed and pinned. Research in the area of steel frame performance and modeling has shown that the accuracy of structural response predictions depends largely on modeling assumptions and, in particular, the modeling of the column-base plate connection. Selection of boundary conditions and the associated design details has a significant influence on the structure response[1]. In the case of large seismic events, column base plate failures have occurred due to the inconsistency between modeling assumptions and the actual demand the connections experience[2], highlighting the need for students to consider the effects of their computational modeling decisions on the building behavior. Experiments bring challenging engineering topics such as this to life, particularly when students are actively involved and collaborating with their peers[3,4]. Often if students don't see it, students don't believe it. In addition, if students don't see the theory applied to realistic engineered systems they don't believe it either[5].

In courses where commercial computational analysis programs are used, students are taught to be skeptical of the computer output, an issue that is a significant source of contention for engineering firms. "With the increased use of the computer, we seem to have gotten lazy about asking the next question. If the printout says something is so, it must be so"[6]. One of the goals of this senior level design and analysis course is to improve students' ability to accurately predict the response of structures subject to a variety of loading conditions. This experiment also supports the course goal of developing critical thinking skills as the students were challenged with considering how the boundary condition details influence the demands on the connections and the overall structure.

Test Specimen:

An 8½ feet tall, three-dimensional two-story steel moment frame served as an ideal structure for students to experiment with and model. The frame is composed of W6x9 columns and beams.

Figure. Two-story Steel Frame, Beam/Column Connection and Column Base Connection

The 18" thick concrete floor diaphragms are sized to result in realistic natural frequencies for the first few modes of the frame. The columns are connected to the laboratory concrete floor through 1" thick steel base plates and four 5/8" diameter bolts spaced at 5.25" from the column centerline in the strong axis direction and 4.25" from the column centerline in the weak axis direction. The weight, including the beams and columns, is 6056 lbs. at the 2nd floor and 5887 lbs. at the 1st floor. The centerline dimensions of the frame are 50.5" and 51.5" for the 1st and 2nd floor heights, respectively, and 54" and 71.4" for the width in the column weak-axis direction and strong axis direction, respectively.

Student Hand Calculations and Computational Models:

One of the core precepts of each analysis course is that students are required to check the analysis program results by hand in order to validate the computer output. This often involves simplifying the analysis to a few degrees-of-freedom that can quickly be checked by hand, i.e. allowing only 1 translational degree of freedom per floor of the building. Once the simplified model is validated (1 DOF/ floor), a 3 dimensional analysis of the structure can be conducted where each node in the computational model has 6 DOF, 3 translational and 3 rotational. Students can then use the computational model to run parameter studies to check the influence of variables and in order to choose the most appropriate model.

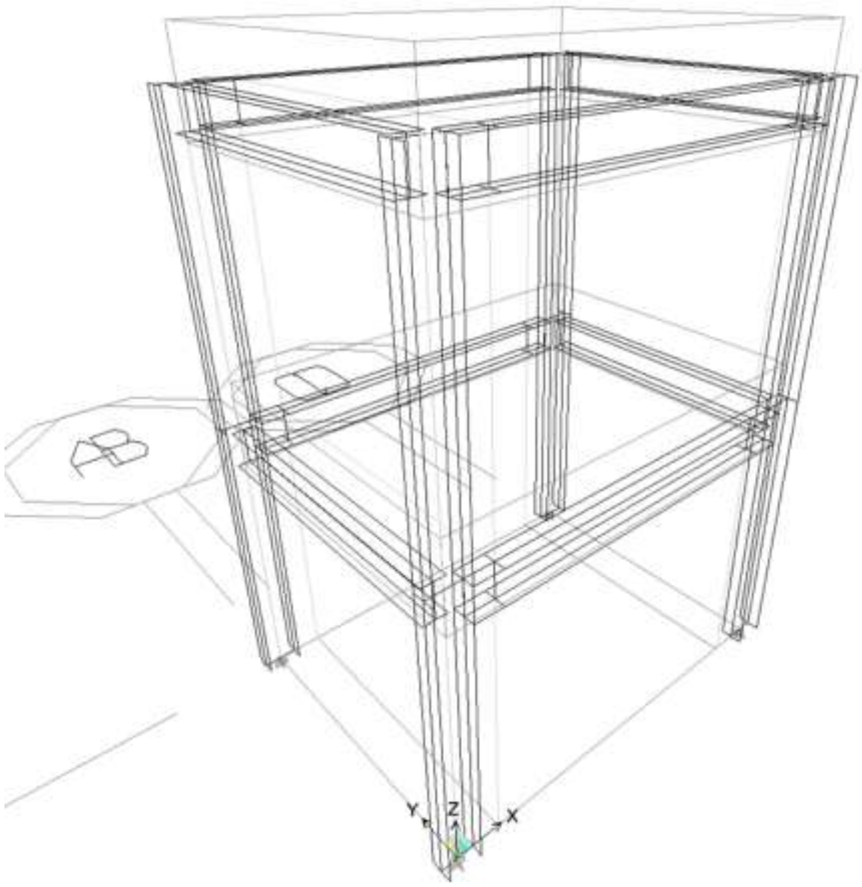

Figure. Student Three-dimensional Computational Model of Two-Story Steel Frame[7]

This simple two-story frame is a good example. Allowing one translational degree of freedom per floor simplifies the lateral stiffness to $12EI/h^3$ for each column where E is the modulus of elasticity, I is the column moment of inertia, and h is the column centerline height. This results in a 2x2 stiffness matrix and a 2x2 mass matrix that can quickly be solved using a calculator. Restraining all DOF's in the computational model except for one translational DOF per floor should result in a match to the hand calculated values, this allows for a check of the computational model input variables that affect the structure mass and stiffness.

Students performed parameter studies to determine the appropriate boundary conditions for the steel frame, varying the column base connections from a fixed condition to a pinned condition. The results are summarized in the table below in the form of a column stiffness coefficient, x, calculated by dividing the story stiffness by EI/h^3 for each of the four columns.

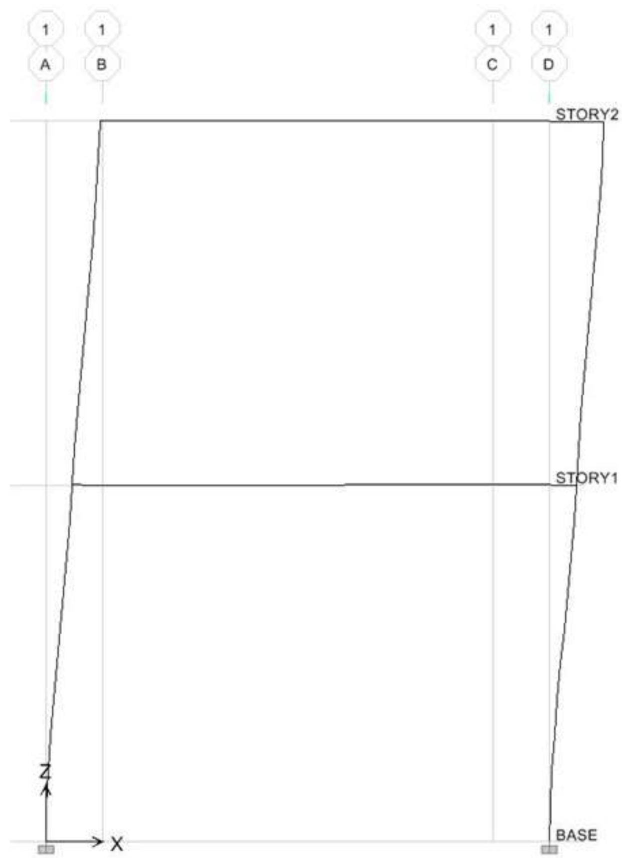

Figure. Two-Story Frame Model Displaced Shape with Fixed Boundary Conditions

Table. Two-Story Frame Column Stiffness Coefficient, *x*

	Column Stiffness Coefficient, *x*, 2nd floor	Column Stiffness Coefficient - *x* 1st floor
Fixed Base Model	3.35	5.45
Pinned Base Model	2.34	1.50

Forced Vibration Testing (FVT)

Next, students performed forced vibration testing (FVT) to experimentally determine the boundary conditions at the base of the steel frame. The FVT was implemented with a linear shaker that loaded the structure with a dynamic sinusoidal excitation, and an accelerometer that measured the response[8]. The linear shaker was placed on top of the concrete slab at the second level to excite the structure at the natural frequencies in the column strong axis and column weak axis directions. The story shear, V, was calculated from the story displacement, U, and the story force, F. The story displacement was calculated by dividing the measured story accelerations by the square of the angular natural frequency, ω [9]. The story force was calculated using Newton's 2nd Law, $F=ma$, where m is the floor mass and a is the measured floor acceleration. With the shear force at each level and the displacement of each level, the lateral stiffness of each level was determined through statics. The values for natural frequency, floor acceleration, floor displacement, story shear, and column stiffness coefficient are shown in the table below.

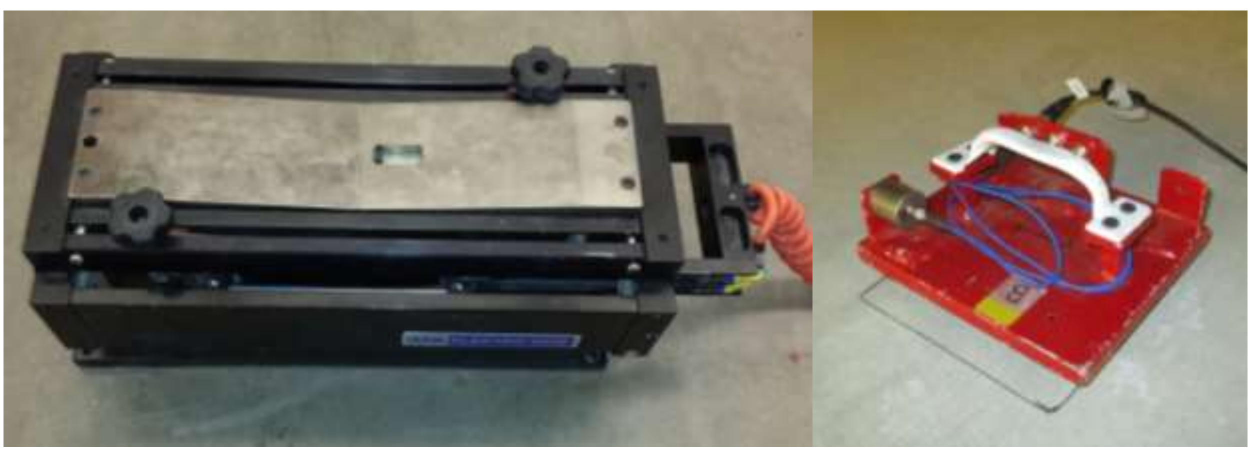

Figure. Linear Shaker and Accelerometer

Table. Force Vibration Testing (FVT) Results and Column Stiffness Coefficients

	Natural Frequency	Floor Acceleration (*a*)		Floor Deformation (*U*)		Story Shear Force (*V*)		Column Stiffness Coefficient (*x*)	
	f_n (Hz)	2nd flr (g)	1st flr (g)	2nd flr (in)	1st flr (in)	2nd flr (lbs)	1st flr (lbs)	2nd floor ("*x*"EI/h^3)	1st floor ("*x*"EI/h^3)
Weak Axis	3.59	0.025	0.014	0.0079	0.011	150.1	84.24	11.10	10.65
Strong Axis	5.94	0.020	0.010	0.0027	0.0028	120.8	59.81	3.19	4.34

A column stiffness coefficient of 12 results from a fixed column base and rigid beams. For loading in the column weak axis direction, the column stiffness coefficient was close to 12, while in the column strong axis direction the results were much lower, highlighting the beam flexibility and rotation at the base connection.

Prior to conducting the dynamic experiments, students were asked whether they thought the steel column base connection was closer to a fixed connection or closer to a pinned connection, 80% of the class considered a fixed condition to be more realistic and 20% of the class considered a pinned connection to be more realistic. As seen in the table, the structure response is closer to a fixed base than a pinned base, however, neither idealized boundary condition is correct.

Revised Computational Models

At this point students were challenged with developing a more accurate computational model to match the experimental results. The students' FVT experiments illustrated that neither of the idealized boundary conditions accurately captured the behavior of the column base connections in the column strong axis direction. A fixed base was appropriate in the column weak axis direction, however, in the column strong axis direction the students needed to model a boundary condition between a fixed base and a pinned base. As a result the students modeled the column bases in the column strong axis direction with a pinned connection along with a rotational spring. The stiffness of the rotational spring was first estimated based on the moment arm between the base plate bolts and the column centerline, this resulted in a value of 50,000 K-in/rad. Iterating on that initial value to match the FVT results, the students converged on a column base rotational spring stiffness of 70,000 K-in/rad. The table below compares the students' fixed base model, pinned base model, FVT results and a pinned base model with rotational spring stiffnesses of 70,000 K-in/rad. The results clearly show that the modified pinned base boundary condition model accurately predicted the two-story frame response.

Table. Computational Model, FVT and Calibrated Computational Model results in the Column Strong Axis Direction

	Column Stiffness Coefficient - x 2nd floor ("x"EI/h^3)	Column Stiffness Coefficient - x 1st floor ("x"EI/h^3)
Fixed Base Model	3.35	5.45
Pinned Base Model	2.34	1.50
FVT	3.19	4.34
Pinned Base Model w/ rotational springs (70,000 K-in/rad)	3.21	4.32

Conclusions:

One of the goals of this undergraduate engineering analysis course is to help students build a healthy sense of skepticism toward computer output. This can be uniquely emphasized by having students compare their computational model results with experimental results; testing structures often brings theoretical concepts to life and for many students 'seeing is believing'. Detailed computational models are often created to design and predict the response of a structure, however, boundary conditions are typically idealized to simplify the analysis. In order to expose students to realistic boundary conditions, students were challenged with predicting the response of a two-story steel frame, experimentally capturing the steel frame response and modifying the computational models to align with the experimental results. The students discovered that the steel column connections to the concrete laboratory floor were between the idealized boundary conditions they had been exposed to in their analysis courses.

Experiments where students are actively involved and collaborating with their peers bring challenging engineering topics to life, resulting in a deeper level of critical thinking. The students enjoyed the opportunity to compare their computational model predictions of the steel frame response to the dynamic experimentation. This exercise encouraged students to validate their computer analysis results with hand calculations as well as consider how to appropriately model boundary conditions that often fall somewhere in between the idealized conditions they focus on in their undergraduate courses. In addition, students experienced first-hand how design details affect the boundary conditions and the overall structure demand and behavior.

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