Structural Health Monitoring Of A Stadium For Evaluating Human Comfort And Structural Performance

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STRUCTURAL HEALTH MONITORING OF A STADIUM FOR EVALUATING HUMAN COMFORT AND STRUCTURAL PERFORMANCE

by

HASAN OZERK SAZAK
B.S. Middle East Technical University, 2009

A thesis submitted in partial fulfillment of the requirements For the degree of Master of Science in the Department of Civil, Environmental and Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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ABSTRACT

Light and rapid constructions as well as considerations such as improved line of sight and increased capacity for modern stadium structures make them vulnerable for vibration serviceability problems. These problems are also observed at convention centers, large shopping malls, concert halls and ballrooms. Especially when the individuals in a crowd are involved in some sort of coordinated motion, this type of loading creates the most potential for high levels of vibration. In order to understand the causes of vibration, vibration levels, service and safety levels, Structural Health Monitoring (SHM) can be implemented to track and evaluate performance of a structure during events such as games at football stadia. SHM becomes a critical need especially when decisions such as repair and retrofit are to be made for the structure. The main objectives of this study are a) to determine the impact of vibration to human comfort levels; b) to identify dynamic loading for the coordinated motion; c) to determine the structural performance by means of a detailed model validated using experimental data. In order to achieve these objectives, a football stadium was monitored for three years to establish the vibration levels during different games and different events in each game such as goals, interceptions, playing a particular song. It is seen that certain events and long periods of playing particular songs induced vibration levels that are at the threshold of human comfort based on the design codes. To simulate the crowd motion due to this song, a laboratory study was designed and conducted to experimentally determine the forcing functions due to jumping with the rhythm of the song. The spectral analysis of the stadium data and the song also revealed that the first mode frequency of the stadium and the dominant frequency of the music are very close, creating
resonance conditions. Further investigative studies were conducted by developing a finite
element (FE) model of the stadium, which was validated using the results of the modal analysis
from the ambient vibration data. Subsequently, the FE model was employed to simulate forcing
functions obtained from the laboratory studies to explore the vibration levels, dynamic response
as well as the response of the structure when it is retrofitted by additional elements. In addition,
different aspects of model development, with respect to the physical model of the stadium were
outlined in terms of design considerations, instrumentation, finite element modeling, and
simulating dynamic effect of spectators. Finally, the effectiveness of the retrofit by adding
elements to the steel structure of the stadium was explored by simulating the crowd motion with
the FE model.
To my family, for their endless support in each and every step of my life.
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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Sport events are followed by many people in all around the world and have become a major industry. Especially for popular games such as soccer, basketball and football, the number of fans is rising each day. Improvements for light and rapid constructions and considerations such as improving line of sight and increasing the capacity for modern stadium structures create possibility for vibration serviceability problems. Especially when the individuals in a crowd are involved in some sort of coordinated motion, this type of loading creates the most potential for high levels of vibration. As dynamic effect of people gain more importance, the incidence of problems with displacements and vibration serviceability started to increase.

Structural Health Monitoring (SHM) techniques with methods of data evaluation can be implemented to understand the performance of a structure during games such as football. In order to understand the causes of human induced vibration and vibration levels, occurring service and safety levels, SHM becomes important especially when repair or improvements on the structure are considered for the structure.

When the football stadium considered for this study was erected, everything was designed according to existing codes. However during the first game, it was sensed that the vibrations could be higher than expected during some events. The design for safety has been
much better understood with material behavior, structural configurations and expected loads than
design for serviceability and human comfort. For example, the dynamic loading at the student
section cannot be easily predicted as it was the case for this stadium. In order to understand
dynamic behavior of the structure and implications to human comfort and safety, researchers
designed and implemented a SHM for the stadium and the data were analyzed to address the
issues.

1.2 Objective and Scope

The objective of this thesis is (Figure 1) to analyze the human induced vibrations
occurred during football games in a stadium and to analyze the vibration levels with respect to
human comfort levels as defined by international codes. After analyzing the vibration data,
experimental modal analysis and finite element model development are performed to understand
the dynamic characteristic of the investigated section in detail. Later, in order to create a
dynamic load model that can simulate the spectators’ jumping during the games, laboratory
experiments are conducted. Researchers are made to jump on a platform with the same song
played during the games to create a similar effect as they were in stadium. Developing the finite
element model and obtaining the forcing function with laboratory experiments, dynamic loading
simulations are applied to the finite element model to create the jumping effect of spectators in
stadium. Finally, an improvement in finite element model by retrofit application is studied and
suggestions to decrease the vibration level were presented.
The scope of work includes analyzing the stadium vibration data for human comfort levels for different games and different events. By conducting modal analysis with experimental data sets, findings are used to understand dynamic characteristic of the stadium. To characterize the source of the vibration due to jumping of spectators, laboratory experiments are completed and jumping effect of people is identified accordingly. Combining the outcomes from modal analysis and laboratory experiments, finite element model is created to simulate the effect of jumping during the games in the stadium. Dynamic characteristics of investigated section obtained from finite element model are updated with the monitoring data sets collected from the field. Simulating the real vibrating situation with data sets obtained from laboratory experiments,
the behavior is evaluated with and without structural modifications along with interpretations of improvements in structural response.

1.3 Literature Review

Excessive vibrations created problems at several stadiums around the world. These problems were investigated by the researchers in different aspects. The following sections will give a brief overview about the stadium monitoring, human comfort and jumping load factor.

1.3.1 Stadium Monitoring

Pernica (1982) conducted one of the earliest stadium monitoring applications during a 3 hour rock concert to see how the audience response affects the dynamic behavior of a stand area having a fundamental frequency below 5 Hz. Investigated area was subjected to foot stamping and hand clapping at repetition frequencies between 2 and 3 Hz. Dynamic live loads and static live loads were calculated, resulting resonant and non-resonant behaviors were presented and compared with design loads specified in the National Building Code of Canada.

Reynolds and Pavic (2002) conducted modal testing of a sports stadium grandstand at a soccer stadium in the UK. During the modal testing, APS113 shaker and six reference accelerometers were used. Entire modal test and preliminary estimation of the modal properties of the structure were presented in the paper. Also results from the modal testing were compared
with the results of a finite element analysis. At the end discrepancies between the FE model and the modal test results were highlighted and some explanations were given.

Taun (2003) conducted a monitoring application to the upper deck of University of Wisconsin Football Stadium. Three accelerometers were used and vibrations induced by coordinated rhythmic jumping of spectators were monitored for several football seasons. In his paper, spectral analyses of the field data were conducted to identify the predominant vibration mode shape of the investigated section. With the help of outcomes from assessing the group effect based back-calculated load, spectral densities were studied.

Caprioli et al. (2005) monitored Giuseppe Meazza stadium in Milano to investigate some vibration problems related to movements of people attending big events. At the beginning a few measurement location inside the stadium and a number of points in the nearby buildings were monitored. These buildings were chosen that significant vibrations were perceived during particular events, especially concerts. After the measurements were analyzed it was seen that the frequency of the vibration was same with the frequency content recorded in the stadium. Another outcome was about the vibration levels that reached on the stadium. It was stated that the vibration level posed a series of problems in terms of structural behavior.

Reynolds and Pavic (2006) published another paper for modal testing and in-service monitoring of a large contemporary cantilever grandstand in the United Kingdom. Monitoring was completed during an international soccer game where the capacity of the stadium was full. Modal parameters during the stadium was empty were also investigated and in service monitoring results were described accordingly. It was found that crowd occupation can
significantly alter the modal properties of a stadium because of the changes due to varying crowd configuration.

Reynolds et al. (2007) reported the results from the dynamic testing of the Kingston Communications Stadium. They implemented modal testing using two different methods. One of them was shaker modal testing based on frequency response function measurements. This study determined vertical modes of vibration of the seating decks. The other one was ambient vibration testing, which was carried out to estimate global fore-and-aft and side-to-side modes of vibration, could not be excited sufficiently using artificial shaker excitation. These two studies determined modes of vibration both for vertical seating deck modes and horizontal fore-and-aft and side-to-side global modes.

1.3.2 Human Comfort

Salyards and Hanagan (2007) reported the implications of generating crowd enthusiasm by coordinated crowd motion. Monitoring was accomplished in a large football stadium, which was monitored for vibration during several football games. During these games, a portion of a popular song with a very enticing beat was played in the stadium. They identified that those particular incidences showed a marked increase in vibration levels with respect to the remaining typical activities. The experimental monitoring procedure and results were discussed to draw attention to the potential for crowd-induced rhythmic motion during events and classified according to their serviceability levels.
Caprioli et al. (2007) conducted vibration level evaluation for two different standards, i.e. ISO2631 and BS6841, which have different frequency weightings and differences in quantities used to identify the vibration. Results depending on the efficiency in detecting anomalous vibration levels were discussed. The comparison was performed considering different events in the Giuseppe Meazza Stadium in Milano and also comparing the same event in two different structures; Red Hot Chili Peppers concert in the Milano and Manchester Stadium.

1.3.3 Jumping Load Factor

Yao et al. (2006) described the direct measurement of human induced forces due to jumping on a moving force platform. Focusing on the issue of jumping on a flexible structure that can move perceptibly, a unique test rig was developed to permit a person to jump on an idealized single degree of freedom system with variable natural frequency and mass. Analysis results from jumping in the region of half the natural frequency and of the natural frequency were presented. Also, the effect of contact ratio, which is the ratio of time in contact with the platform/period of jumping time was determined in the study.

Racic and Pavic (2009) proposed a mathematical model to generate synthetic vertical force signal induced by a single person jumping. It was presented that more reliable temporal and spectral features of the real jumping loading could be replicated than the existing half sine models coupled with Fourier series analysis. The model they presented offered the development for synthetic narrow band jumping loads.
Salyards and Firman (2010) investigated the ability to estimate dynamic loading effect in more reasonable obtainable acceleration response of the structure during the events. They used experimental testing to investigate the accuracy and sensitivity of load estimation method for consideration when applying this method to large scale structures. During these experiments simple floor structure was subjected to dynamic forces generated by small groups and result were presented accordingly.

1.4 Organization of Thesis

After reviewing the studies presented in the literature section, it was understood that human induced vibrations in stadiums and characterization of human effects on vibrations were observed at other structures as well. Structural health monitoring was utilized to track vibration levels and understand the problem in these studies. However, detailed studies in terms of understanding the structures dynamic characteristics after validating with experimental data sets, dynamic loading models from laboratory tests implemented with finite element models and investigations of structural improvements on the finite element model were not extensively studied.

Following all the issues listed in the literature review, the thesis continues with the start of data analysis on the basis of event capturing and human comfort level identification. Later, the FE model is developed and verified with modal analysis of experimental data sets. Next, laboratory experiments are conducted to understand the human-structure relation with jumping
of people and to come up with a forcing function to be applied to the FE model. Finally, dynamic loading simulations on the FE model and the effect of structural improvements are analyzed.
CHAPTER 2: MONITORING OF A STADIUM FOR HUMAN COMFORT

ANALYSIS

2.1 Description of the Stadium

The stadium monitored in this research is located at South-East part United States (Figure 2). The construction was completed in 2007 and the stadium was opened in the same year. The stadium is a steel frame structure sitting over 25 acres and has approximately 45,000 seating capacity.

Figure 2 : Location of the Football Stadium
The monitoring was performed at two student sections: Section 1, which was one of the corners of the stadium, and Section 2, which was the section next to corner section (Figure 3). The reason to choose student section to monitor was the expectation of higher vibration levels than other sections of the stadium. Students mostly get more excited during the games and also the university band was located close to the monitored section, which created another reason for the students become more excited.

Figure 3: General View of the Stadium
The two sections in Figure 4 do not have the same dimensions in general. Section 1 was one of the corners of the stadium; seating sections in that part are narrowing down frame sections (Figure 4). Rear ends of Section 1 have 60 ft opening and about 55 ft height while the front ends have about 15 ft opening and 7.5 ft height. As a side note; dynamic analysis are using finite element model were only conducted for Section 1 since this was the original section under consideration.

Figure 4: General View of the Investigated Sections

The difference of Section 2 from Section 1 is not only the location of sections. Section 2 (Figure 4) has a uniform structure with a 30 ft opening consistent in the rear and front opening of
this section. There was not any narrowing down so there was no difference between the front and rear opening lengths.

The Section 2 was retrofitted after investigations of induced vibrations students creating excessive trampoline effect while they were jumping during the games. After inspections and analysis, excessive deformations and high vibration levels were identified and it was decided to place extra I-beams to existing beams to retrofit the sections (Figure 5).

![Figure 5: Retrofitted Section](image)

Additional retrofit beams were connected to existing beams with bolts with one foot spacing. It has a wider flange length but shorter web depth compared to the existing one (Figure 6). With the retrofit, an increase in inertia of the section was achieved with the objective of reducing beam displacements and vibrations.
2.2 Monitoring Equipments and Instrumentation

2.2.1 Design Considerations

Stadium structure is mainly made up of two components according to seating places, which are upper and lower sections. For the instrumentation, accelerometers were placed both at upper section (Figure 7) and lower section (Figure 8) to monitor these sections. Before the instrumentation, locations of the accelerometers were carefully selected and instrumentation was completed afterwards (Catbas and Gul, 2009).

Figure 6: Retrofit Cross-section
Figure 7: Location of Upper Section Accelerometers

Figure 8: Location of Lower Section Accelerometers
The objective of choosing the locations of the accelerometers was to monitor each different element type of the structure such as primary elements (main girders), secondary elements (floor girders) and tertiary elements (stringers). To identify the characteristic of these elements in investigated sections, twelve accelerometers were placed in vertical, lateral, and longitudinal directions to measure the vibration levels in three different directions. Middle points of the beams and stingers were chosen for the sake of maximum vibration. Eight of these accelerometers were in the upper section (Figure 9) and the remaining four accelerometers were in the lower section (Figure 10).

Figure 9: Location and Direction of Upper Section Accelerometers
2.2.2 Sensors and Data Acquisition System

Because of low frequency vibration of civil structures, high sensitivity PCB 393C (Figure 11) accelerometers were considered appropriate to monitor the stadium. These accelerometers were designed to collect vibration measurements at low frequencies with a usable frequency range of 0.025 to 800 Hz, sensitivity of 1000 mV/g and range up to 2.5 g peak. These accelerometers were connected to the data acquisition system with insulated cables running over the frames.
Instrumentation of stadium was a team work where the installation of sensors and cabling to the data acquisition system was a critical issue because of the elevation and framing of the structure. Accelerometers were connected to steel frames with magnets however, in case of magnets may not function; a special safety system (Figure 12) was also planed and applied for redundancy. That method was a combination of hot glue and cable tie connection. Magnets used to install the accelerometers, had small gaps in their middle sections, which allowed to researchers fill with hot glue. Next, before the hot glue froze in the middle part, a cable tie placed in it. So when glue cooled down, an extra safety mechanism occurred with the magnets. Finally, the small cable tie system was connected to the frame with extra cable ties.
For data collection, digital data acquisition was performed using VXI-Agilent Technologies and PCB data conditioner (Figure 13), which had sixteen input channels in each system. Sampling rate was defined as 100 Hz because in stadium structures, frequency range of interest was mainly around 0-30 Hz.

Data was collected before, during and after the game to obtain a general response of the stadium in each period. For the data collection durations, ten minute intervals were defined and approximately twenty five data sets were collected in each game. In addition to acceleration data acquisition, video were recorded and notes were taken.
2.3 Monitored Games

Monitoring was applied to the stadium for the past three years and during that period eight different games were monitored. Six of the games monitoring studies were carried out at Section 1 and the last two game monitoring studies were performed at Section 2 where analysis results from the four of the eight games are presented as follows:

1. Game 1 – Section 1 10.20.2007 (Home Win)
2. Game 2 – Section 1 (Homecoming) 11.03.2007 (Home Win)
3. Game 3 – Section 1 (Homecoming) 11.08.2008 (Home Loose)
4. Game 4 – Section 2 11.21.2009 (Home Win)
Two of these games were “Homecoming games,” which is a tradition of welcoming families and alumni to the game and activities held in the week of the game. These games were chosen specifically due to high number of people attending to these games.

While data collection was being conducted, notes at game events were taken to relate these events to the vibration data. There were some obvious events during the game that should be analyzed carefully such as stamping of the spectators, interception, touchdown and “Zombie-Nation”. The “Zombie-Nation” is the stamping of spectators with the popular song “Zombie-Nation”. It was one of the critical events during the games that all the spectators started jumping and stamping when they heard the song. Since the spectators jumped and stamped with this beat, the motion became a coordinated motion that created higher vibration levels.

2.3.1 Event Capturing

Vibration monitoring was carried out before, during and after the game to see the general configuration of the vibration levels during the game. Figure 14 presents sample data where twelve accelerometers capture the same event with different amplitudes at their particular locations. Figure 15 illustrates five of the twelve accelerometer readings, which are chosen specifically to show the highest vibration levels and different directions.
Figure 14: Sample Raw Acceleration Data

From Figure 14, it can easily be observed that there was an event starting around the ninth minute (~540 sec) of the interval captured by most of the accelerometers. There were two accelerometers, seventh and eighth accelerometers, which were located on the main girder in lateral direction, seemed to read nearly zero vibration. Also another event or jumping occurred at the beginning of the data set, however, it was not very obvious in channels nine, ten, eleven or twelve. This can be interpreted as a group of spectators jumping in the upper section.
2.3.1.1 Game 1

Game 1 was played in 2007, which was the year home team won most of the home games among the three of monitoring years. It was reported more than 45,000 spectators attended this game that filled the entire stadium. Before the game, when nearly no one was in the stadium, it was expected to see approximately zero vibration at the structure. However, still relatively significant vibration can be observed as shown in Figure 15.

![Figure 15: Game 1 - Before Game Data](image)

Cheering of spectators as “defense” was also an important event for a small period of time and captured during the data collection. The duration of this event was not very long
however it can be considered an important event such that during this stamping, spectators cheered “defense” and at the same time hit to stands and created a maximum of 0.52 g vibration as shown in Figure 16.

![Figure 16: Game 1 - De-fense Cheering](image)

Event capturing and correlating with the measured vibration levels was another goal of the monitoring. By capturing the events and vibrations simultaneously, it would be calculated which events created high vibration levels and whether these vibration levels were critical. For the first game, three important events for the game were captured together (Figure 17) in one of the data sets. Interception, touchdown and the popular song “Zombie Nation” were these
captured events. Interception, which was an instantaneous event, created an excitement on the spectators and they started to jump and stamp just afterwards. This instantaneous event created a vibration level around 0.25 g. Touchdown, which spectators could follow that it was going to happen, created quite similar level of vibration but a little higher than interception that had a value of 0.27 g. The last but the most important event for that data set was the popular song “Zombie Nation”. This event was mostly enjoyed by all spectators and they started to jump when beat was played during the game. Jumping of the spectators with the beat led to a synchronized, coordinated motion effect on the structure. That coordinated motion created a high value of vibration level, which was around 0.45 g.

Figure 17: Game 1 - Event Capturing
For the first game, another event was also captured. That event was the kick-off, which created a higher vibration level than the touchdown that was scored previously. Figure 18 shows the difference in the vibration levels. Mostly, the kick-off event did not create such a high vibration level, however, the touchdown just before the kick-off was very exciting for the spectators. With that excitement spectators cheered and jumped with the kick-off again and created around 0.55 g level of vibration while the touchdown created around 0.45 g vibration level.

Figure 18: Game 1 - Touchdown and Kick-off after Touchdown
2.3.1.2 Game 2

The second game in 2007 was a homecoming game. Since it was the first homecoming game for the home team, all of the homecoming festivities were held first time on campus. Such a big event brought so many spectators to the stadium that over 46,000 people attended the game. Data collection started about half an hour before the game started, so when before game data was investigated (Figure 19), more significant vibration was observed than the first game’s before-game data.

![Graphs of vibration data](image)

Figure 19: Game 2 - Before Game Data

During the second game event capturing with note taking also applied. Touchdown, defense cheering and popular song event was captured again. During the game because of the
crowd and good play, spectators mostly give high responses to the events. One of those events, they created the highest level of vibration (Figure 20). It was captured in one of the data sets during a popular song event. When spectators heard the “Zombie-Nation” song, they started to jump respectively in such a way that the jumping created two high values in the same data set respectively, which were around 0.51 g and 0.60 g.

![Graph showing vibration levels for different channels](image)

**Figure 20: Game 2 - Popular Song**

In the same data set, another significant event was caught. That event was de-fense stamping between 256 sec and 265 sec. When this was closely inspected (Figure 21), it was seen that de-fense cheering created a vibration level of 0.43 g in the first channel. When other channels for the same time period were analyzed to catch the same event, it was seen that
channel four and channel seven captured the event but with less in magnitude of vibration. Furthermore, channel nine and eleven did not show any indication for the de-fense stamping. From that case, it can be concluded that there was stamping only by the spectators of the upper section.

![Acceleration Data for Channel 1](image)

**Figure 21: Game 2 - De-fense Cheering**

### 2.3.1.3 Game 3

Game three, which was played in 2008, was also a homecoming game attended by around 42,000 spectators in the stadium. That game was not as crowded as the homecoming game in 2007. During the game, event capturing was also completed again; however, home team did not
play that well, one touchdown happened during the game popular song played for on time after the touchdown. The only touchdown excited the crowd in such a way that a vibration of 0.49 g was captured (Figure 22).

On the other hand, playing the popular song after the touchdown to increase the excitement of the spectators was not very successful that only a 0.35 g vibration level was recorded. From the same location, channels ten and eleven it was understood that spectators at the lower section were also accompanied to jumping and created a significant vibration but less than the spectators at the upper section.
2.3.1.4 Game 4

Game 4 data sets were collected from section 2 and a sample data set is shown in Figure 4. That section was the retrofitted section. Although low vibration levels were expected due to structural improvements, some peaks of high acceleration levels were captured. In some data sets, researchers were also able to catch the effect of events on the spectators also. During game four, popular song, touchdown and again popular song were captured respectively in a particular data set (Figure 23). Although the same beat was played before and after the touchdown, reaction of the spectators was different. In Figure 23, accelerometer readings from different sensors are presented from previous game readings. When maximum values of vibration levels were analyzed, it was seen for the popular song event, before the touchdown, as 0.23 g. Three minutes after that song home team scored a goal and that touchdown created 0.38 g value of vibration. Just after the touchdown, popular song beat was played again but this time spectators created nearly 1.5 times of the previous popular song vibration level, which was around 0.36 g. The reason of this significant difference was the touchdown event between the two popular song events, which was explained as when team scored, people got more excited and stamped stronger.
2.3.2 General View of a Game

Until now, only particular event capturing or focusing to main channel of the collected data sets investigated. In this part, a general view of the first game (Figure 24) are analyzed and explained. After specific investigations of the sensors, more detailed analyze of the game was conducted and general behavior of the spectators obtained. There were some obvious peaks in the data sets, which can easily be correlated with the notes taken during the game, i.e. game start, touchdown, and popular song. From general view it can also be concluded which section of the stadium give higher or lower response to events. It was more obvious for the lower section spectators jumped and stamped higher according to upper section spectators during the game. In
most of the events lower section accelerometers read an equal or higher vibration level than upper section accelerometers.

Figure 24: Maximum Acceleration Data for Game 1

2.4 Human Comfort Analysis of the Games

2.4.1 Human Comfort Idea

There are many effects of vibration to human identified by researchers such that short term annoyance, reduced motion control, impaired vision and discomfort are some of those effects. There are also the long term effects of vibration but since football game events were
short in duration and the events occurred during games were not a daily repetitive event, short
term effects were considered at this point.

The current international standard, evaluation of human exposure to whole-body
vibration (ISO 2631-1, 1997), outlined methods for quantifying vibration exposure. This
standard suggested quantitative guidelines for human response to vibration in terms of comfort
levels and health guidance caution zones.

2.4.2 Procedure

For the human comfort analysis, before evaluating the vibration levels according to
human comfort, experimental acceleration values had to be converted to weighted acceleration as
mentioned in the ISO 2631-1. However in order to apply formulas related with the weighted
acceleration, time-domain accelerations were converted to frequency-domain accelerations by
Fourier transformation.

After obtaining frequency-domain data sets, filtering function, which was obtained by
multiplication of filters in frequency-domain, was used to obtain weighted accelerations in
frequency-domain. To obtain the filtering function, different filters defined by ISO 2631-1 were
multiplied with each other. These filters were:

- Band-limiting filter
  - High pass filter
  - Low pass filter
- Acceleration-velocity transition filter
- Upward step filter
2.4.2.1 Band Limiting Filter

Band-limiting was a two-pole filter that has high pass (Equation 1) and low pass (Equation 2) filters with Butterworth characteristic. The Butterworth filter was a method of electronic filter design. This type of filter was designed to have flat frequency response in the pass band.

*High pass filter:* A high-pass filter was an Linear Time-Invariant filter that passes high frequencies well but reduces the amplitude of frequencies lower than cutoff frequency (Figure 25).

\[
|H_h(f)| = \sqrt[4]{\frac{f^4}{f^4 + f_1^4}}
\]

(1)

where \( H_h(f) \): High pass filter function

\( f \): Specified frequency range

\( f_1 \): Cutoff frequency for high pass filter specified by ISO 2631
Figure 25: High Pass Filter

*Low pass filter:* A low-pass filter was a filter that passes low frequency signals but reduced the amplitude of signals with frequencies higher than cutoff frequency (Figure 26). Its formulation can be seen in Equation 2.

\[
|H_1(f)| = \sqrt{\frac{f_2^4}{f^4 + f_2^4}}
\]

(2)

where \( H_0(f) \): Low pass filter function
\( f \): Specified frequency range

\( f_2 \): Cutoff frequency for low pass filter specified by ISO 2631

In low pass filter, it was observed that filter affects the frequencies more after 100 Hz limit and this affect increased as the frequency went further. In acceleration data analyses, since data analysis focused on a lower frequency band where human induced vibrations were more critical, the effect of low pass filter could not be observed very much.

**Figure 26: Low Pass Filter**
2.4.2.2 Acceleration-Velocity Transition Filter

Acceleration-velocity transition (Equation 3) was the proportionality to acceleration at lower frequencies and to velocity in higher frequencies as can be seen in Figure 27:

$$|H_t(f)| = \frac{f^2 + f_3^2}{f_3^2} \sqrt{f^4 Q_4^2} \sqrt{f_4^4 Q_4^2} \frac{f_4^2 Q_4^2}{f^2 + f_4^2 (1 - 2 Q_4^2) + f_4^4 Q_4^2}$$

(3)

where $H_t(f)$: Acceleration-velocity filter function

$f$: Specified frequency range

$f_3$: Cutoff frequency for acceleration-velocity transition filter specified by ISO 2631

$f_4$: Cutoff frequency for acceleration-velocity transition filter specified by ISO 2631

$Q_4$: Resonant quality factors specified by ISO 2631
2.4.2.3 Upward Step Filter

Steepness was approximately 6 dB per octave in this formulation and it was proportional to jerk. The formulation (Equation 4) and the function can be seen below (Figure 28) below.

\[
|H_s(f)| = \frac{Q_6}{Q_5} \times \frac{f^4 Q_5^2 + f^2 f_5^2 (1 - 2 Q_5^2) + f_5^4 Q_5^2}{f^4 Q_6^2 + f^2 f_6^2 (1 - 2 Q_6^2) + f_6^4 Q_6^2}
\]

(4)

where \( H_s(f) \) : Upward step filter function
\( f \): Specified frequency range

\( f_5 \): Cutoff frequency for upward step filter specified by ISO 2631

\( f_6 \): Cutoff frequency for upward step filter specified by ISO 2631

\( Q_5 \): Resonant quality factors specified by ISO 2631

\( Q_6 \): Resonant quality factors specified by ISO 2631

---

**Figure 28: Upward Step Filter**
In the filter equations, the parameter given by “f” defines the frequency range from 0 to 50 Hz in a linearly increasing manner. 50 Hz stemmed from the Nyquist frequency where sampling rate defined as 100 Hz and the Nyquist frequency as 50 Hz, half of the sampling rate. Rest of the parameters was defined by ISO 2631-1 as can be seen in Table 1:

Table 1: Parameters of the transfer functions of the principal frequency weightings

<table>
<thead>
<tr>
<th>Weighting</th>
<th>Band-Limiting</th>
<th>Acceleration-velocity transition (a-v transition)</th>
<th>Upward step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f1</td>
<td>f2</td>
<td>f3</td>
</tr>
<tr>
<td>W_k</td>
<td>0.40</td>
<td>100</td>
<td>12.50</td>
</tr>
<tr>
<td>W_d</td>
<td>0.40</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>W_f</td>
<td>0.08</td>
<td>0.63</td>
<td>∞</td>
</tr>
</tbody>
</table>

After having filtering parameters, the total weighted acceleration function (5) was obtained by the multiplication of “f” parameter with filter functions. When total weighing function was checked with ISO 2631-1 (Figure 29), the match was apparent.

\[ H(p) = H_h(p) * H_t(p) * H_f(p) * H_s(p) \]

(5)
Finding the weighting function, experimental data sets were multiplied with the weighting function. However, since all the filtering process was in frequency-domain, data sets were converted to frequency-domain from time-domain with the help of Fast Fourier Transformation (FFT). With the conversion and multiplication process, the weighted acceleration values obtained. In order to move on the calculation steps for human comfort evaluation, weighted accelerations were converted back to time-domain with inverse Fourier transformation.

After obtaining the weighted acceleration values in time-domain, in order to relate vibration levels with human comfort levels defined in ISO 2631-1, researchers used root mean square (R.M.S.) formulation (6) to calculate weighted R.M.S. accelerations where \( \tau \) is the integration time for running average and recommended as 1 sec in ISO 2631-1.
Resulting vibration levels were classified according to a chart (Table 2) given in ISO 2631-1. However, acceptable values of vibration magnitude for human comfort depend on many factors. Therefore strict limits for comfort levels were not defined.

<table>
<thead>
<tr>
<th>R.M.S. Value (m/s²)</th>
<th>Corresponding Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.315</td>
<td>Not Uncomfortable</td>
</tr>
<tr>
<td>0.315-0.63</td>
<td>A Little Uncomfortable</td>
</tr>
<tr>
<td>0.5-1</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td>0.8-1.6</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>1.25-2.5</td>
<td>Very Uncomfortable</td>
</tr>
<tr>
<td>&gt;2</td>
<td>Extremely Uncomfortable</td>
</tr>
</tbody>
</table>

2.4.3 Human Comfort Analysis

For the human comfort analyses, four graphs are presented in this section to explain the correlation between raw data, R.M.S. value of the data and corresponding situation it refers (Catbas et al., 2010). Event capturing and interpretations related to the results are explained accordingly.

Figure 30 shows the analyzed data in previous section for Game 1 and the resultant R.M.S value chart after human comfort calculations. It can be seen from Figure 30 that as the vibration level increases, R.M.S. value also increases. When R.M.S. values are checked with
corresponding situation table (Table 2), it is observed that interception created fairly uncomfortable situation, touchdown created an uncomfortable situation and popular song created uncomfortable situation for the spectators. For popular song event the comfort level can also be identified as very uncomfortable situation. The difference about the comments stemmed from the duration of the event. For this data set, it can be considered as uncomfortable situation because the duration, where the maximum level of vibration occurred, affected for a short period of time.

Figure 30: Game 1 – Vibration Levels at Interception, Touchdown & Popular Song
Figure 31 (data from Game 2) and Figure 32 (data from Game 3) were chosen to show an observation of time duration effect on vibration. In Figure 31, popular song event with a maximum vibration level of 3.83 m/s² was captured. When the human comfort analysis was applied to the data set, 1.89 m/s² of R.M.S. value was identified, which corresponded to a very uncomfortable situation for the spectators. However, when another data set was investigated, a touchdown having a maximum vibration level of 4.75 m/s² and 1.29 m/s² R.M.S. value was identified in Figure 32. That value corresponded to uncomfortable situation for the people in the stadium.
Even having a higher value of acceleration in the raw data, touchdown event had less in R.M.S. calculation result. That is because the duration of the synchronized motion of the spectators. When touchdown occurred, people reacted for about seven seconds, they jumped and stamped respectively. However when popular song was played nearly all of the spectators jumped in a coordinated for thirty seconds and created the comfort difference in the situation.

![Graph showing Raw Data - Channel 1 and R.M.S. - Channel 1](image)

**Figure 32: Game 3 - Vibration Level at Touchdown**

The last experimental data set analyzed was collected from the retrofitted part of the stadium, which is section 2 in Figure 4. The structure of the retrofitted part was different than section 1 and also there was a gap between section 1 and section 2 to create structural
decomposition and to decrease the temperature effect on the structure. Because of the structural difference, comparison of two sections might not give a clear idea about retrofitting. However for the sake of understanding the effect of retrofit on the basis of human comfort, data set collected from that section was analyzed for human comfort. When events in Figure 33 analyzed, it was understood that popular song event did not create much vibration as seen in previous years as observed at other sections. Observed human comfort level could be specified as fairly uncomfortable situation where the same event was defined as very uncomfortable in previous data sets.

Figure 33: Game 4 - Vibration Level at Popular Song
Investigating other data sets from the same game, it was understood not all the data sets were such low vibration levels. Figure 34 shows a data set from the same year and same game with the previously shown graph. As two graphs compared, different vibration levels and different human comfort levels were obviously identified. Seeing such high vibration levels and very uncomfortable situation for spectators, although the data set was from retrofitted section, made us to investigate the structure in detail. Regarding issues are discussed more in the following chapters.

Figure 34: Game 4 - Vibration Level at Popular Song
2.5 Findings and Results

After analyzing the four different games from different seasons, it was seen that vibration levels were based on the types of events occurring during the games. The vibration created at the moment of event could reach to vibration levels for the structure such as high as 0.60 g (~5.9 m/s²). Although somewhat subjective, it was observed that these vibration levels were important for human comfort. It was identified that, not only the vibration levels were important but also the duration of the event while considering the human comfort was important (Table 3). It was observed that a 4.75 m/s² value of vibration because of a touchdown created uncomfortable situation. On the other hand, 3.83 m/s² value of vibration level occurred during popular song and created very uncomfortable situation for the spectators. Having a low level of vibration but less comfortable situation during popular song is because of being a synchronized motion and having longer duration.

<table>
<thead>
<tr>
<th>Game 1</th>
<th>Event</th>
<th>Max Acceleration (m/s²)</th>
<th>Max RMS (m/s²)</th>
<th>Comfort Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interception</td>
<td>2.45</td>
<td>0.63</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Touchdown</td>
<td>2.65</td>
<td>0.72</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Zombie Nation</td>
<td>4.41</td>
<td>1.44</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>Game 2</td>
<td>Zombie Nation</td>
<td>5.00</td>
<td>0.79</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Zombie Nation</td>
<td>5.89</td>
<td>0.93</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Zombie Nation</td>
<td>3.83</td>
<td>1.89</td>
<td>Very Uncomfortable</td>
</tr>
<tr>
<td>Game 3</td>
<td>Touchdown</td>
<td>4.81</td>
<td>1.29</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Stamping</td>
<td>3.63</td>
<td>0.78</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>Game 4</td>
<td>Stamping</td>
<td>2.26</td>
<td>0.69</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Zombie Nation</td>
<td>1.86</td>
<td>0.96</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Zombie Nation</td>
<td>4.32</td>
<td>1.78</td>
<td>Very Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Touchdown</td>
<td>2.84</td>
<td>1.44</td>
<td>Uncomfortable</td>
</tr>
</tbody>
</table>

Table 3: Events, Vibration Levels and Corresponding Comfort Levels
The other issue to be investigated in monitoring of the stadium was the effect of retrofitting the beams. When the results were checked, it was observed that they were varying for the type of event and also response of the spectator to the event. Touchdown event for the non-retrofit part had 0.45 g (~4.4 m/s²) value and popular song had 0.60 (~5.9 m/s²) g as maximum levels of vibration. On the other hand in the retrofit part, touchdown event had 0.30 g (~2.9 m/s²) and popular song event had 0.44 g (~4.3 m/s²) value as the highest level of vibration. It should be noted that this comparison is for two different sections (curved corner section (Section 1) with no retrofit and straight back section (Section 2) with retrofit). When games and events are analyzed separately, it might be considered that retrofitting was effective, however even from the same day and same type of event, different levels of vibration could be captured. That brought the idea to investigate the retrofitted section in more detail with modal analysis and to explore the dynamic characteristics for the retrofitted section also.
CHAPTER 3: FINITE ELEMENT DEVELOPMENT AND VERIFICATION

3.1 Development of the Finite Element Model

This chapter will describe the development of the finite element model of the stadium structure. With a finite element model that represents the real structure as close as possible, it will be possible to simulate the dynamic effects due jumping of the spectators in the stadium.

The development of the finite element model of the stadium was performed with a particular sense. The first item that needed to be completed was to go over the blueprints and also pictures of the stadium. Once these documents were reviewed, a model could be developed in AutoCAD 2009. A great deal of time was spent on the review of the construction documents. The AutoCAD 2009 model was developed using lines to represent the different frame sections. The lines were then placed in different layers to represent the corresponding frame section. That was done to ease the process of importing the AutoCAD 2009 model into SAP2000. Once the CAD model was completed, it was then imported into SAP2000. Figure 35 shows a flow chart of the modeling process and Figure 36 shows the elevation view of the stadium from blueprints and from FE model. In Figure 36, stringers elements were also shown in FE model figure which were not shown in the CAD drawing. These elements were shown in detail in other blueprints and CAD drawings.
Figure 35: Flowchart of Model Development
A finite element model having 365 frame elements, 609 nodes and 379 links was created. There were some considerations due to connections of frames, frame sizes and boundary conditions. First of the considerations was the connection of stringers to other frames. Stringers were connected to beams from top as they were sitting on beams. Even though these members
are connected on top of each other, they still act as one member because of the bolt connections between them. In the stadium, stringers are also connected to each other with standing places but in the FE model seating places were not defined. To simulate these two considerations about stringers in SAP2000, joint connections were placed at these nodes and link connection assumptions were made. To accomplish this, frame members were divided at the point of connection. This action created two nodes. These nodes were then connected by a joint connection. By this, stringer-beam connections and stringer-stringer connections were simulated to work together. Figure 37 shows the member connections in stadium. Seating places are on top of stringers and stringers are connected to each other by seating places. Figure 38 shows how the issue was resolved in SAP2000 by using rigid link connections.

Figure 37: Picture of Stadium and Members Sitting on Top of Each Other
Second consideration was the type and size of the frames. Researchers did not have all the blueprints and due to that some of the frames exist in stadium may not fully match with the structural drawings, i.e. cross bars at the rear opening of the stadium structure was shown as I beams in the drawings; however, it was identified that they were box section in existing structure (Figure 39). In such cases, frames were measured in the stadium and members having the closest dimensions were used in FE model studies.
Figure 39: Difference between Existing Stadium Structure and Blueprints

Last consideration was the boundary conditions. Since corner section of the stadium structure was modeled for finite element studies, continuity of the frames with other sides of the stadium should be satisfied. In order to simulate the continuity with other frames springs were used at the sides of the FE model where frames connected to other section frames (Figure 40). The spring constant was chosen to be 50 kip/in based comparison of various values and engineering judgment.
After properties were assigned to the frame members, a systematic approach was followed for the model check. First, the extruded views of the FE model elements were visually inspected for the orientation of the members and verified with field inspections (Figure 41).

Figure 40: End Conditions
Next, displacements of the elements were checked if they were in a reasonable range (Figure 42). To accomplish this, one of the beams used in the model was taken out and another model was created with boundary conditions with pin and fixed connections at both ends and displacements were checked under live load. A live load of 100 psf was applied, defined in Florida Building Code (2004), after multiplied with the tributary area where the beam was taking the load from. Subsequently, the beam displacement from the model created for the investigated section of the stadium was also obtained and the results (Table 4) showed that the displacements were between the two boundary condition results.
Figure 42: FE Model Deformed Shape under 100 psf Loading

Table 4: Displacements for Different Boundary Conditions

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>Beam Deformation Check Under 100 psf Live Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix-Fix</td>
<td>0.45 in</td>
</tr>
<tr>
<td>Pin-Pin</td>
<td>2.34 in</td>
</tr>
<tr>
<td>Stadium FE Model</td>
<td>1.72 in</td>
</tr>
</tbody>
</table>

Final check was modal analysis check, where the FE model was compared with the results obtained from experimental modal analysis results. This will be explained in detail in the following section.
3.2 Experimental Modal Analysis

Experimental modal analysis was carried out by analyzing different data sets from different games and different years. Using output data sets, system identification methodology used to analyze experimental data sets by using complex mode indicator functions (CMIFs) together with the random decrement (RD) method, where modal parameters were identified. CMIF used the unscaled multiple-input multiple-output data sets generated using the RD method for parameter identification (Gul and Catbas, 2008).

Modal properties of the stadium structure system under ambient loading were obtained by using RD and CMIF methods together. From the ambient vibration data, by using the RD technique, the unscaled impulse response of the system was computed. Taking the fast Fourier transform (FFT) these impulse responses are converted to unscaled FRFs. After obtaining the unscaled FRFs, they are fed to the CMIF algorithm to obtain the modal parameters. Finally, using the modal parameters the unscaled flexibilities and frequencies were obtained (Figure 43).
When experimental data sets were analyzed, it was seen that each data set showed similar dynamic characteristic and the first mode of the structure, which was a vertical mode, can be identified in most data sets. Three different data sets from three years were analyzed to obtain the distribution first mode of the structure. Due to spectator load, which means an extra mass for the structure, it was seen that the first mode varied between 2.1-3 Hz (Figure 44) depending on the weight of spectators over the investigated section with a damping ratio of 4-5%. After the
distribution was analyzed with probability density function and logarithmic curve fitting, it was more realistic to assume the stadium’s first mode around 2.45 Hz.

![PDF of Frequency of First Mode](image)

Figure 44: Frequency Distribution for the First Mode

3.3 Verification of the Finite Element Model

After experimental data sets were analyzed and modal frequencies were obtained, they were used to calibrate the FE model. When frequencies from the FE and experimental data
analysis were compared, it was seen that they were in a close range. Certainly they were not exactly same; however the difference was in an acceptable range.

After last calibration steps due to boundary conditions applied, for the sake of verification, modal assurance criterion (MAC) values were checked. MAC is the providing measure of consistency (degree of linearity) between two modal vectors, where \( x_k \) the \( k \)th mode shape of the modal analysis and \( y_j \) is the \( j \)th mode shape of the finite element model (Allemang and Brown, 1982).

\[
MAC(x_k^*, y_j) = \frac{|x_k^T y_j^*|^2}{(x_k^T x_k)(y_j^T y_j)}
\]

MAC values had extra importance for modal assurance because the investigated section was not uniform or custom elevated structure and the FE model could not be fully calibrated. Results gave a high number of modes in 20 Hz range. For that reason, MAC values checked according to data analysis result of field data and 0.94 MAC value obtained for the first mode between first mode frequencies of experimental data and finite element model. Difference in first mode frequencies of experimental data and finite element model was 6%, which was an acceptable difference. Second mode also had high MAC value and small differences in modal frequencies. When transversal and longitudinal motions took place more in movement of structure, MAC values started to decrease. It should also be mentioned that some of the MAC values between experiment and FE model are low. One reason for this may be the low spatial resolution of the sensor grid especially for lateral directions. As vertical motion got more dominant, as in seventh and eighth mode, MAC values started to increase again. Since the
forcing function, which was spectator load, was vertical, the important modes of the structure were the vertical modes, the first two modes. When mode shapes were investigated in finite element model similar mode shapes were identified. The results for frequencies were not exactly same however; the difference was deemed acceptable (Table 5).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Motion Type</th>
<th>Experimental Modal Analysis Freq.</th>
<th>Finite Element Model Freq.</th>
<th>% Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Vert.</td>
<td>2.45 Hz</td>
<td>2.59 Hz</td>
<td>6</td>
<td>0.94</td>
</tr>
<tr>
<td>2nd</td>
<td>Vert.</td>
<td>4.89 Hz</td>
<td>4.12 Hz</td>
<td>15</td>
<td>0.98</td>
</tr>
<tr>
<td>3rd</td>
<td>Vert. &amp; Trans.</td>
<td>7.49 Hz</td>
<td>8.06 Hz</td>
<td>7</td>
<td>0.56</td>
</tr>
<tr>
<td>4th</td>
<td>Trans.</td>
<td>12.73 Hz</td>
<td>10.85 Hz</td>
<td>14</td>
<td>0.48</td>
</tr>
<tr>
<td>5th</td>
<td>Vert. &amp; Trans.</td>
<td>12.92 Hz</td>
<td>11.66 Hz</td>
<td>9</td>
<td>0.62</td>
</tr>
<tr>
<td>6th</td>
<td>Vert., Trans. &amp; Long.</td>
<td>13.08 Hz</td>
<td>14.85 Hz</td>
<td>13</td>
<td>0.93</td>
</tr>
<tr>
<td>7th</td>
<td>Vert., Trans. &amp; Long.</td>
<td>14.61 Hz</td>
<td>16.28 Hz</td>
<td>11</td>
<td>0.79</td>
</tr>
</tbody>
</table>

When experimental data sets were analyzed for modal analysis (Figure 45), it was seen that the first mode was vertical movements of the lower seating places of the investigated section. Second mode was also vertical motion of lower seating places. Third mode of the structure was similar with the first mode, which was vertical motion of the lower section, however adding to first mode also upper seating places’ vertical and transversal motion was observed. Fourth mode was the transversal motion of the upper section, however vertical motion of upper and lower sections together. In fifth mode, upper section moved in vertical direction and lower section showed transversal motion. In sixth mode, complex motion of upper and lower section existed. Vertical, longitudinal and lateral motion could be observed at the same time. When the seventh mode analyzed, which was another complex mode, it was seen that similar
motion with sixth mode exists. Lower and upper sections moved in vertical, longitudinal and lateral direction.

Figure 45: 1st Mode Shape of FEM
Figure 46: 2\textsuperscript{nd} Mode Shape of FEM

Second Mode: $4.12$ Hz
Vert. Motion of Lower Section

Figure 47: 3\textsuperscript{rd} Mode Shape of FEM

Third Mode: $8.06$ Hz
Vert. & Trans. Motion of Upper Section and Vert. Motion of Lower Section
Figure 48: 4th Mode Shape of FEM

Fourth Mode: 10.85 Hz
Trans. Motion of Upper Section & Lower Section

Figure 49: 5th Mode Shape of FEM

Fifth Mode: 11.66 Hz
Trans. Motion of Lower Section & Vert. Motion of Upper Section
Sixth Mode: 14.85 Hz
Vert., Trans. & Lat. Motion of Upper & Lower Section

Figure 50: 6th Mode Shape of FEM

Seventh Mode: 16.28 Hz
Vert., Trans. & Lat. Motion of Lower & Upper Section

Figure 51: 7th Mode Shape of FEM
Another check for the model validation was the comparison of vibration levels under dynamic loading. Experimental results gave a maximum vibration level of 0.6 g (5.89 m/s²). To validate the FE model one of the experimental data sets from jumping load tests was chosen as the loading time-history forcing function. When dynamic loading was applied the stadium model, results were in the reasonable range. These outcomes are discussed later in the following chapters.

3.4 Summary

In this chapter finite element (FE) model development and comparison of the FE model with experimental results were discussed in detail. First, development of the FE model using structural drawings and inspection data from site visits was explained. Steps followed for the issues of frame connections, element sizes and the boundary conditions described. After that, model checks in terms of extruded view check, displacement check for loading cases and modal analysis procedures were explained. In order to obtain modal frequencies CMIF and RD methods used together and modal frequencies in the range of 0-20 Hz, was identified. Finally verification of the FE model was explained. Modal frequencies obtained from the field experiment data analysis and FE model was compared by using the modal assurance criteria.
CHAPTER 4: LOAD MODEL DEVELOPMENT

4.1 Analytical Studies

There have been several studies for reliable and practical descriptions of the loading coming from people jumping by measuring the interface forces between the ground and the feet. Typical measured continuous force time-history functions in the vertical direction were assumed to simulate single peak pulses (Figure 52).

Figure 52: Example of a Vertical Jumping Force Record Due to a Single Person Jumping
There have been a number of investigators focusing on this subject. Bachmann and Ammann (1987) assumed that series of identical half-sine wave pulses may be represented by measured jumping force pulses. However, measured data could not fit the symmetric half-sine function. It was suggest that for dynamic analysis such a set of periodically appearing half-sine pulses can be presented more efficiently if expressed in terms of Fourier series with the fundamental harmonic, having a frequency identical to the jumping rate (Ji and Ellis, 1994; Ellis and Ji, 1994; Bachmann et al., 1995). However even the sum of the six Fourier harmonics, which was the maximum number reported in the literature, could not match adequately enough the original half-sine forcing function for all contact times (Figure 53).

Figure 53: Half-sine Wave Function and Sum of the Six Fourier Terms to Represent the Jumping Force-time History (Racic and Pavic, 2009)
4.2 Laboratory Studies

To obtain a better model for spectators jumping in the stadium, a small scale experiment was conducted in the laboratory. Researchers were made to jump on a beam in groups of one, two or three people (Figure 54) while the popular song “Zombie Nation” was played at the same time. The aim of this study was to measure force difference between the persons’ standing position and jumping with a song, which means with a specific frequency, and later to obtain a factor by dividing the effect of jumping to the normal body weight.

Figure 54: Three Person Jumping Position
The beam used during jumping experiments was a 4 feet C-channel type beam. It was instrumented with four load cells and three accelerometers. Transducer Techniques load cells having a capacity of 5000 lbs each were placed under the corners of the C-type beam (Figure 56). However, flange thickness of the beam was so small that 4x4 square thin plates were welded to the corners of the beam to provide full contact between the beam and the load cells (Figure 55).

![Figure 55: Welding of 4x4 Plates to the Corners](image)

![Figure 56: Location of the Load Cells](image)
For accelerometer selection, since the girder was expected to have higher frequency range, first, a simple frame model was created with SAP2000 and first mode frequency obtained from the software. Later, obtaining the first mode frequency around 80 Hz, PCB 603C01 type of accelerometer was chosen for the test. The accelerometer has a frequency range of 0.5 to 10k Hz, a sensitivity of 100 mV/g and a measurement range of 50 g. Three accelerometers were placed under the girder, one in the middle and the other two arbitrarily to get the maximum vibration and many modes of structure (Figure 57).

![Figure 57: Location of Accelerometers](image)

Data acquisition was performed by using National Instruments: NI-SCXI 1001 chassis for signal conditioning, NI-SCXI1520 and NI-SCXI 1314 for strain gage input and NI-SCXI 1531 for accelerometer input. Sampling rate was defined as 100 Hz for load cells and 2048 Hz for accelerometers. Data sets were collected of about 40-45 seconds each, where only about 25-30 seconds was jumping.
4.3 Results of Laboratory Studies

4.3.1 Frequency Domain Analysis

The experiment was conducted with three different persons in different combinations, and data sets were analyzed accordingly. Before obtaining the jumping load factor results, acceleration data sets and force data sets were checked in frequency domain analysis for resonance effect. The song played during the experiment “Zombie-Nation” had a frequency of 2.37 Hz, (Salyards and Firman, 2010) so it was expected the jumping frequency would have a close value. When frequencies of the forcing functions were analyzed, it was observed that frequency of the jumping varied in a range of 2.16 Hz to 2.41 Hz and the flexible range was due to the imperfection of the human body. On the other hand, the frequency of the beam used during
the experiments was around 80 Hz. That result showed that jumping frequency was away from the frequency of the beam and the results were not affected by resonance.

![Finite Element Model of the Beam Used for the Load Tests](image)

**Figure 59: Finite Element Model of the Beam Used for the Load Tests**

The beam finite element model was also used to verify the match between experimental and model results. In order to simulate jumping loading and verifying results, same jumping model could be applied to a general stadium finite element model. From the finite element model (Figure 59), first mode was identified at 89 Hz. Results for the modal analysis showed that first mode, which was obtained from the FE model, was close to the first mode of experimental results, which was found to be around 80 Hz. The difference was due to boundary conditions, where plates were used to make the beam stand on force cells in a good position.

Damping of the beam was also calculated. The stadium structure damping was defined as 4-5% in previous chapter, and to use the same jumping factors obtained in laboratory tests, beam and stadium structure should have close damping values. If the damping was high in the beam,
acceleration values might have been low or if the damping was low, acceleration values might have been high. In both cases, it would not represent the same situation as stadium structure does.

Damping of the beam was calculated with half-power bandwidth method, which is a commonly used method for damping calculations (Figure 60). Similar to the stadium structure, the beam’s damping ratio was found around 5% after applying the half-power bandwidth method.

![Figure 60: Half-power Bandwidth Method](http://www.mfg.mtu.edu/)
4.3.2 Time Domain Analysis

After the verification of ineffectiveness of resonance by frequency domain analysis, the effect of jumping was calculated from the experiment results. During the experiments, a single person, two persons or three persons were made to stand and jump on the beam and data sets were collected simultaneously.

The main objective of laboratory jumping tests was to create a jumping model that can simulate the jumping of the spectators during the games. To create the model, data coming from the load cells were normalized (Figure 61) and applied to the FE model as a time-history function.

Figure 61: Jumping Effect of a Single Person
In order to verify the validity of the time-history application, acceleration data collected from experiments were compared with the FE model acceleration results. Loading was applied in vertical direction as the people's own weight obtained from experiments. However, data sets were collected with high sampling rates in both experiment and the FE analysis. On the other hand jumping of persons with the popular song had a frequency around 2.2-2.4 Hz and the beam used during experiments, 80 Hz. In order to get rid of high frequency sampling effects, a special zero-phase 100 Hz low pass filter was applied to both experimental and the FE results. After the filter application, good correlation was obtained, as can be seen from Figure 62. Also when the standard deviations of the absolute values of two functions, experimental and the FE model results, were analyzed, it was seen that standard deviation of the FE model results was 0.104 g and standard deviation of experimental results was 0.092 g, a 10% difference. Maximum value of experimental data was 0.123 g and FE model result was 0.127 g, and minimum value of experimental data was -0.104 g and FE model result was -0.086 g, which can be considered as an acceptable correlation between experiment and FE model results.
4.4 Summary

In this chapter, the loading function that was used as the forcing function in the stadium FE model was developed. First, background of the study with a brief literature review was presented. Later, the laboratory experiment with the beam used as standing places, the data acquisition system and sensors used to collect data and the jumping configurations was described. The first mode frequencies of the test beam and the FE model were observed to be close. Finally, the response of the beam FE model with the forcing function obtained from the experiment and the actual beam response were compared.
CHAPTER 5: EVALUATION AND ASSESSMENT OF FINITE ELEMENT MODEL UNDER DYNAMIC LOADING

5.1 Stadium FE Model under Dynamic Loading

In this chapter, simulations with dynamic loading and the change in the dynamic responses related to change in the structure composition by retrofit application are discussed. With the studies completed in previous chapters, dynamic loading in finite element models are applied to obtain the vibration levels and dynamic characteristics with the FE model of corner section of the stadium. Later on, retrofitting is applied to the FE model and the effects of improvements are investigated.

In order to see the spectators' jumping effect in the stadium FE model, the loading function obtained in previous chapter (Figure 64) was applied to the structure in time-history analysis. Load was calculated as if the stadium capacity were full. In the existing stadium, seating places are connected to stringer directly and those stringers are connected to beams so the load is distributed to the stringers in gravity direction (Figure 63).
In the investigated stadium spectators were not jumping in a perfectly coordinated manner, which meant not everyone would jump up and fall down at the same time. Stadium loading forcing function was chosen according to that criterion. Figure 61 explained the realistic and non-realistic situations for jumping of the spectators. In order to apply a dynamic loading to the FE model, realistic part of the data set obtained during the jumping load test (Figure 64) was used as the forcing function of the spectators.
When experimental data sets were collected during the games, vibration level of 0.6 g acceleration levels could be identified from the accelerometers positioned vertically in the lower seating section. When the results from FE model studies investigated, average 1-g vibration level (Figure 65) was obtained from the node in closer location where field maximum value of vibrations obtained. Results are not expected to match exactly with the experimental data results because of the complexity of the structure, not having a fully updated FE model and especially the difficulty in accurately simulating the forcing function representing people jumping. Yet, the FE model results could be considered to be within an acceptable range for interpreting the
reasons of vibration, the effect of the retrofit, and possibly making decisions about the response of the structure.

![Acceleration Response](image)

**Figure 65: Vertical Acceleration at Lower Seating Section from FE Model**

### 5.2 Stadium FE Model under Dynamic Loading with Retrofit Application

The purpose of developing a FE model with retrofit was to identify the changes in vibration level and dynamic characteristics with increasing the stiffness of the section by implementing the retrofit to structural members. Another aim was improving the first modal frequency with the extra stiffness, so that the frequency of the first mode, which was close to the popular song “Zombie-Nation’s” frequency, would increase and the probability of having a resonance effect would decrease.
In order to see the difference in dynamic responses in time domain and frequency domain, one of the beams used in the stadium with real dimensions was taken into consideration as a preliminary study. After obtaining the results, retrofitting was applied to the same beam as applied at the field in other sections. Dimensions of the retrofit beam were measured during field studies and applications were done accordingly.

5.2.1 Dynamic Loading to Single Beam

As a preliminary study, one of the beams at the stadium structure (Figure 66) was analyzed under dynamic loading. A W16x40 beam, which was used as secondary beam in the stadium structure, was chosen for the study. For the total loading force, the spectators above the beam were considered.
A finite element model was generated for dynamic loading application (Figure 67). The tributary area that the beam took the load from was assumed as a rectangular area with the dimensions of 30 ft x 14.2 ft. Also, a 100 psf design load was used for stadium structures with bleachers according to the Florida Building Code (2004).

Those dimensions and loading case brought a total load of 42.6 kip applied to the beam as point loads because of the connection of the beam with stringers. That load was divided by the number of stringers over the beam and applied to the investigated beam as point loading with a time-history function. Time-history loading function was obtained from the laboratory studies during jumping load tests. When results are analyzed, it was seen that the vibration level for the
middle point of the beam was around 1 g for the investigated part of jumping (Figure 68). This result was obtained as a baseline to be compared with the results of a retrofitted beam.

Figure 67: Finite Element Model of Single Beam and Point Load Application

Figure 68: Vertical Acceleration at the Middle Point of the Beam
5.2.2 Dynamic Loading to Retrofit Single Beam

After analyzing the single beam, in order to understand the effect of retrofit application, a second beam was implemented to the model. The retrofit already exists in some parts of the stadium (Figure 69). To obtain the real application information, dimensions of the retrofit beam was measured and the frame having the closest dimensions attached under the original beam one in the finite element model. The retrofit beam was terminated 1 ft away from the beam connections as per the retrofit application. Two beams were connected to each other with bolts in real structure. In order to simulate the similar connection, rigid links were used in the finite element model (Figure 70).

Figure 69: Retrofit Application from Stadium
Figure 70: Finite Element Model of Retrofitted Beam

Similar approach for force application in the basis of point loading and time history function was used. Depending on the retrofit application, both the response of the middle section and modal parameters of the beam changed.

With retrofit, bringing extra stiffness to structure, vibration level dropped nearly to half, which gave a vibration level of around 0.5 g (Figure 71), whereas, it was around 1 g in no retrofit case. When comparison was completed in frequency domain, it was clear to see that increased stiffness increased the modal frequencies as one would expect (Table 6).
Figure 71: Vertical Acceleration at the Middle Point of the Beam with Retrofit FE Model

<table>
<thead>
<tr>
<th>Mode</th>
<th>Single Beam Case Freq. (Hz)</th>
<th>Retrofit Beam Case Freq. (Hz)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>6.47</td>
<td>9.04</td>
<td>40</td>
</tr>
<tr>
<td>2nd</td>
<td>16.71</td>
<td>22.21</td>
<td>33</td>
</tr>
<tr>
<td>3rd</td>
<td>29.35</td>
<td>37.53</td>
<td>28</td>
</tr>
<tr>
<td>4th</td>
<td>41.13</td>
<td>50.08</td>
<td>22</td>
</tr>
<tr>
<td>5th</td>
<td>51.48</td>
<td>63.34</td>
<td>23</td>
</tr>
</tbody>
</table>

5.2.3 Dynamic Loading to Retrofitted Stadium FE Model

The retrofitting approach has already been applied to another section of the stadium to decrease the vibration level and increase the stiffness. Stemming from the same application in
other sections of stadium, the corner section of the stadium was also retrofitted in the FE model to investigate the effect of retrofit application.

After verifying the retrofit application with a simple beam analysis in previous sections, the same simulation approach to the stadium FE model was implemented. With the dimensions taken from the retrofitted part of the stadium, a similar I-section W10x39, which was the most similar section to measurements from the field, was used for the retrofitting the beams in the same way to how the real structure was improved.

![Figure 72: Retrofit Application in the FE Model](image)

The same forcing function (Figure 64) used in previous studies applied to the retrofitted stadium model in the same manner and results were obtained after the application of the dynamic loading. For the same vertical joint, investigated for non-retrofitted model, results showed that there was a decrease in the vibration level. With the similar forcing function used in non-retrofit finite element model, it was seen the vibration level decreased to approximately 0.5 g average.
level of vibration (Figure 73) from 1 g average vibration level without the retrofit case. The maximum value of the non-retrofitted finite element model was 1.58 g where maximum value of retrofitted finite element model was 1.38 g. Also, minimum value of non-retrofitted finite element model was -1.82 g where minimum value of non-retrofitted finite element model was -1.19 g. When results were investigated for the standard deviation of the absolute values of two results coming from non-retrofitted model and a retrofitted model, it was seen that in non-retrofit results the value was 0.401 and in the retrofitted model case the value was 0.265. As can be seen from these results, there was a decrease in the vibration levels after the retrofit simulation on the corner section under investigation.

![Acceleration Response](image-url)  

**Figure 73**: Vertical Acceleration in Lower Seating Section after Retrofit Application
Retrofit application did not only affect the vibration levels, but also increased the modal frequencies. Table 7 below shows the change in modal frequencies as a result of increased stiffness of the structure. For the first mode, an obvious increase in modal frequency was captured, which displays the actual role of retrofitting. By increasing the stiffness of the structure, first mode, which was the easiest mode to excite, was moved away from the popular song’s frequency, which was 2.37 Hz, and the resonance affect could be mitigated in this case.

<table>
<thead>
<tr>
<th>Motion Type</th>
<th>Without Retrofit Freq.</th>
<th>With Retrofit Freq.</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st mode</td>
<td>Vert.</td>
<td>2.59 Hz</td>
<td>3.31 Hz</td>
</tr>
<tr>
<td>2nd mode</td>
<td>Vert.</td>
<td>4.12 Hz</td>
<td>5.40 Hz</td>
</tr>
<tr>
<td>3rd mode</td>
<td>Vert. &amp; Trans.</td>
<td>8.06 Hz</td>
<td>8.78 Hz</td>
</tr>
<tr>
<td>4th mode</td>
<td>Trans.</td>
<td>10.85 Hz</td>
<td>11.29 Hz</td>
</tr>
<tr>
<td>5th mode</td>
<td>Vert. &amp; Trans.</td>
<td>11.66 Hz</td>
<td>12.04 Hz</td>
</tr>
<tr>
<td>7th mode</td>
<td>Vert., Trans. &amp; Long.</td>
<td>16.28 Hz</td>
<td>16.65 Hz</td>
</tr>
</tbody>
</table>

5.3 Summary

In this section, simulations with dynamic loading and the effect of retrofitting were investigated. First, the single beam used in the stadium structure was analyzed under dynamic loading. Later, the same forcing function was applied after the beam was retrofitted as used in
the stadium in different sections. After obtaining the dynamic characteristics of the two beams, the results were compared in time domain and frequency domain. It was identified that retrofit application was successful in both decreasing the vibration level and increasing the stiffness. Later, the same approach was applied to the investigated corner section of the stadium model. Results from the non-retrofitted FE model were compared with the retrofitted model in the sense of vibration level and dynamic characteristics. Decrease in vibration level and increase in the stiffness, which brought a higher first frequency, was obtained with retrofit application.
CHAPTER 6: SUMMARY AND CONCLUSIONS

A detailed analysis of human induced vibrations on a stadium during different games was conducted after monitoring of the vibrations of the structure over three years. A finite element model was also developed in conjunction with the experimental studies. Later, these analyses were expanded to investigate the effectiveness of retrofit in terms of reducing the vibration levels and modifying the structural dynamic properties.

The stadium was monitored for three years and during that period eight games were monitored. Two different sections were monitored, which are the corner and the uniform sections. Six of the monitoring studies were conducted at the corner (non-retrofitted) section of the stadium and the other two were at the uniform (retrofitted) section of the stadium. Four games were analyzed to investigate different events and the vibrations induced at these events during the games. Data recordings and related notes showed that there were important events for the structure such as stamping, interception, touchdown and popular songs. Inducing a coordinated motion, the popular song was the most important event for the structure. When the spectators jumped together at a constant frequency for a long duration with the popular song, excessive vibration levels were captured. It was concluded that synchronized motions such as spectator jumping during popular songs became important for the structure and created high levels of vibration. During the studies, events mentioned as critical were also analyzed for human comfort. International codes were used to identify the human comfort levels. During human comfort evaluations it was observed that not only the type of events but the duration of events
were also of great importance. It was concluded that, synchronized motion events mostly created uncomfortable or very uncomfortable situation for the spectators as per the ISO 2631 code. Another conclusion was that even when the maximum value of the vibration (raw signal) of an event was not very high, the situation it created for the spectators (RMS signal for ISO 2631) may induce more uncomfortable conditions depending on the duration of the event. That is another reason for popular song event being the most critical event especially when it was played for longer durations.

In order to better understand the dynamic characteristic of the investigated section and apply dynamic forcing functions, finite element model of the corner section of the stadium was developed. Model checks such as deformation checks, boundary condition checks and modal frequency checks were also conducted. The FE model was developed from the available structural drawings and site pictures, and compared with the modal analysis of the data collected from the field by using CMIF and RD methods. Modal assurance criteria were also taken into consideration for the verification of FE model with experimental data sets and reasonable correlation results were obtained with the available spatial resolution of the sensors.

Laboratory experiments were conducted to understand the jumping of the spectators and to develop a dynamic loading function for the finite element model. People were made to jump in the laboratory on a beam along with the popular song played during the games. Different configurations and different number of people were used to simulate the jumping situation as realistically as possible. Obtaining results from load cells and accelerometers used during the experiment, a frame model of the beam was also generated in computer to verify if the same
jumping can be applied in the finite element model. After verifying the computer results with the experimental results, the same simulation approach was implemented for the corner section finite element model.

After obtaining the FE model and dynamic loading functions, these load models were implemented to simulate people jumping in the stadium without and later with structural retrofit. The aim of retrofit application was to decrease the vibration levels. In order to explore the application of retrofitting, first the loading was applied to a single beam used in the stadium structure and the results were analyzed. Next, one of the beams, which were used as retrofitting element in the field, was attached to an existing beam and results were compared with the non-retrofit case. Decrease in vibration levels and increase in modal frequencies were identified with retrofit application. After the single beam studies showing the retrofit application results in decreasing the vibrations, the same approach was followed for the FE model of the corner section of the stadium. After acceleration responses of the non-retrofitted FE model results were checked with the experimental data sets, retrofit beams were inserted into this FE model to explore the difference in structural behavior after retrofitting. The approach of decreasing the vibration levels and increasing the modal frequencies was achieved with retrofit application. The vibration levels dropped nearly to half of its value before retrofitting and modal frequencies increased by nearly thirty percent for the first two main frequencies. With the increase in the modal frequency, stadium’s first mode frequency was moved away from the range of popular song’s frequency and the probability of the resonance was decreased.
LIST OF REFERENCES


