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Model Updating for a Simple Structure against Impact Loading

by

Junaid Farooq

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Department of Civil Engineering

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I want to dedicate this work to my family, who helped me throughout my education. This is likewise a tribute to our best teachers who guided us to go up against the troubles of presence with ingenuity and boldness, and who made us what we are today.

CERTIFICATE OF APPROVAL

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International Refereed Conference Articles

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(Junaid Farooq)

Abstract

Impact loadings (e.g. blast or missile attack) can cause severe damages to structures. There is a growing trend in studying the experimental and analytical behaviors of structures against impact loadings. Such experimental works are very expensive. However analytical approaches can be economical but these are complicated. Also, there is a need of model updating in understanding the relatively real behavior of structures under impact loadings. In current work, model updating for studying the precise response of a simple structure against impact loading is presented.

For this purpose, single storey, single bay prototype structure consists of 550mm high four aluminium columns fixed at steel base plate is tested. Impact load is applied with the help of a calibrated hammer and recorded at the bottom of one of the four columns and the response is recorded at the top of the same column with the help of two accelerometers mounted at the column top and hammer for the response and impact respectively. For a comparative study Finite element modelling of prototype structure is done in commercially available software SAP2000. Numerical response is then compared with that of experimental one. A set of modifiers is updated based on available literature in order to reduce the difference between numerical and experimental responses.

The employment of modern model updating technique to overcome the difference between numerical and experimental response of the structure showed up encouraging results. An average improvement ranging from 17% upto 22% has been observed after updating the selected parameters based upon the literature. It is noted that the difference in the numerical and experimental results can be due to different uncertain parameters of structure but healthy improvement due to nominal change only in Moduli of Elasticity and Poissons ratio highlights their significance. Moreover, the outcomes highlight the significance of realistic consideration for material properties while designing and hence prompts more in-depth study.

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Abbreviations

1 D	One Dimensional
3 D	Three Dimensional
$\ddot{u}\ _g$	Average acceleration at column base
$\ddot{u}\ _t$	Average acceleration at column top
PIA	Peak Induced Acceleration
u_t	Induced acceleration at column top
P_b	Impact load at column base

Chapter 1

Introduction

1.1 Background

Construction of safe and economical structures have always been a constant concern for Engineers. Modern structures face severe damage by different loadings like earthquake, blast, missile attacks, wind etc. Impact loadings are one of the crucial loadings that create catastrophic failure of structures. Impact loadings include blast loadings nearby or inside structures and missile loadings. In order to design the structures against impact loadings, the behavior of structure against these loadings need to be explored. Different investigations have been reported in literature to determine the behavior of structures against these type of loadings.

Figure 1.1 shows the effect of blast load on the adjacent structures. The pressure built up due to the blast propagates in radial direction and activates the inertia of structure which resultantly increases the strain rate abruptly. It has been known that not only the wave pressure but also the ground excitations play a significant role in producing an impact on structure. The loss of human lives and damages to properties costed millions of dollars [1] which was basically the consequence of a bombing incident. Although initial casualties are due to the direct pressure released by the blast, the overall numbers could have been greatly increased by the collapse of structural components. The majority of built buildings are likely to be insecure or likely to minimize the effects of terrorist bombings. The building and planning control authorities are currently identifying the threats associated with the new atmosphere of global terrorism. Therefore, it is important to carry out vulnerability and damage assessment of buildings subjected to blast loads to provide mitigation strategies. As a direct result of the bombing, the Murrah Building sustained significant structural damage. Three intermediate principal columns supporting a third-floor transfer girder on the north side of the building failed. Some of the floor slabs in the bomb's immediate vicinity were also demolished. The amount of visible damage matched the amount predicted by the calculations [34].

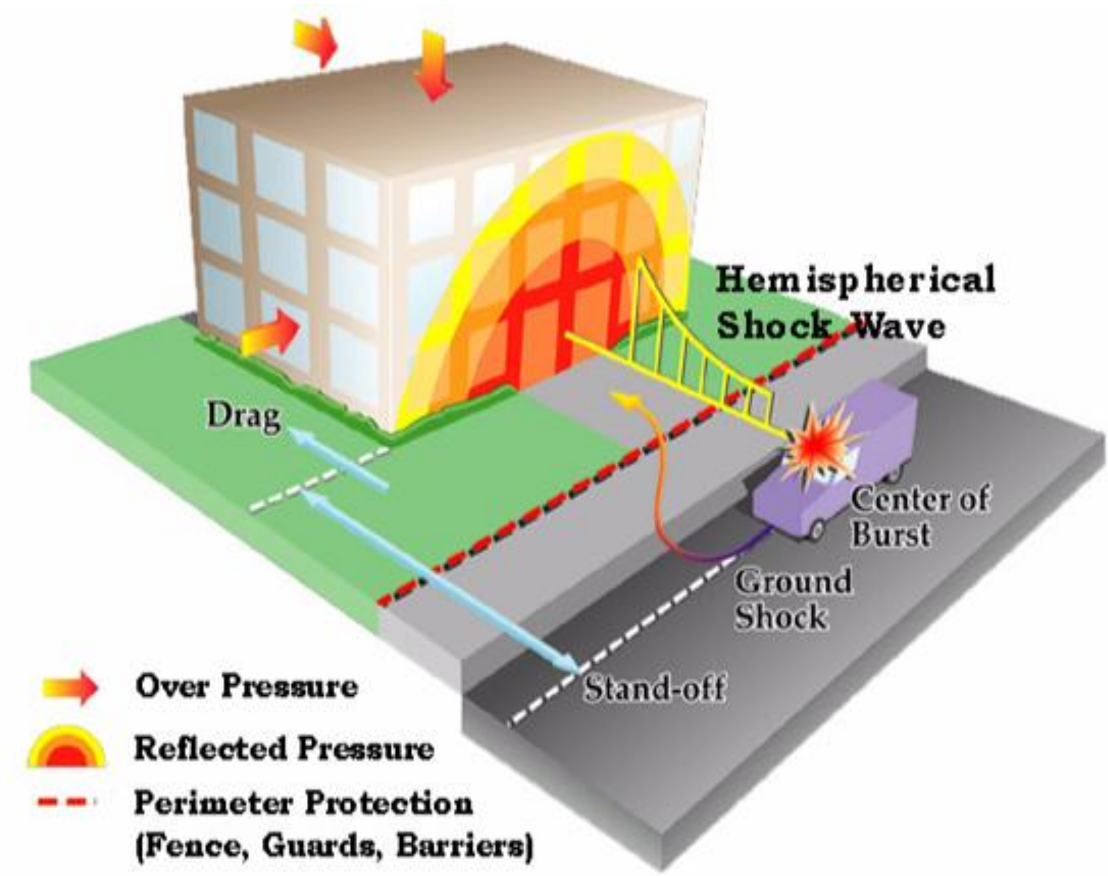

FIGURE 1.1: Impact of blast loading on structure Yalciner [31].

Prototype structures have been used in literature for simulation of impact load on structure. The response of these structures are then inflated to real structures. A simple model was prepared for computing response of real structure [2]. The simple laboratory structure mounted on a shake table was used to measure the response of prototype structure using four accelerometers [3]. The ultra-high performance concrete (UHPC) material formulated on the basis of reactive powder concrete (RPC) was developed and investigated. Columns which were made of these materials was field blast tested. 70% more loading capacity was preserved on a columns with micro steel fiber reinforcement UHPC after detonation of 35 kg trinitrotoluene explosion at a distance of 1.5m standoff, on the other hand only 40% of loading capacity was maintained after the detonation of 8 kg of trinitrotoluene explosion at a distance of 1.5m standoff.

A full scale bridge model was prepared using SAP2000 to study the dynamic behavior of structure [2]. A researcher proposed a 3D finite element model by using LS-DYNA and SAP2000 for modelling of reinforced concrete plates subjected to blast loading [4]. The dynamic response of mortar-free interlocking structure as studied by applying the impact loading at base of prototype structure [5].

Techniques of model updating is about updating a finite element model of a structure so that it can assume higher accuracy of structure dynamics. Quite a few methods of structural model updating have been introduced and this topic is currently under study in various sectors. Most of these studies focused on approaches such as optimal matrix updating, sensitivity-based parameter estimation-based parameter estimation, algorithms for assignment of Eigen-structure and methods for updating neural-networks. An improved sensitivity-based parameter updating method is proposed [6]. The sensitivity-based methods are widely used methods for FE model updating due to their good performance to reconstruct the measured response quantities, such as natural frequencies and mode shapes, etc. Response surface methods for finite element modelling was used [32]. Genetic algorithms calculation were used for updating parameters of the finite element modelling by optimizing the surface response equation. A statistical algorithm for the detection of structural damage was proposed using MSE (Modal Strain Energy) sensitivity for the damage detection process based on ambient vibration measurements, where operational mode shapes are the only data accessible [7]. Updating parameters are the most important in finite element model usually these variables are taken into account in standard model construction [8].

1.2 Research Motivation and Problem Statement

Impact loadings (e.g. blast or missile attack) can cause severe damages to structures. There is a growing need to investigate the experimental and analytical behaviors of structures against impact loadings. These experimental works are very expensive. Analytical approaches are economical but may not give the realistic results without experimental investigations. An economical and simple 3D frame structure is acquired. Behaviour of simple 3D frame structure is explored by using hammer impact loading. Thus the problem statement is as follow.

"It is of great concern to design systems that have greater resistance to extreme dynamic/impact loading. Understanding the response of structure under different conditions is of utmost requirement during both design and execution phase of construction. Difference in anticipated and actual response questions the structural stability. Hence the problem needs to be studied".

1.2.1 Research Questions

The current era lacks in several different aspects in this particular domain which are needed to be investigated. This specific research is carried out to investigate the following questions in particular:

1. What are the major parameters which help in the model updating techniques?
2. What specific structural parameters are to be analyzed in this study?
3. What are the causes of difference in numerical and experimental results?
4. To what extent the differences can be minimized?
5. Does this technique encourages further in-depth study?

1.3 Overall Goal of the Research Program and Specific Aim of this MS Research

The overall objective of the research program is to precisely investigate the 3D response of full scale structure against impact loading in laboratory.

"The specific aim of this MS research work is to investigate the dynamic response of a prototype 3D frame structure under Impact loading in laboratory".

1.4 Scope of Work and Study Limitation

Prototype 3D frame structure is considered for experimental testing. Fixed base will be provided. Response in terms of acceleration-time, velocity-time and displacement-time histories will be recorded. Finite element modeling is carried out for numerical testing. Study limitations include the use of simple 3D frame prototype structure, two accelerometers only (one at the prototype structure and other at the hammer), simplified boundary conditions and commercially available finite element modelling and analysis program SAP2000.

1.4.1 Rationale Behind Variable Selection

It is evident form the literature that there are several uncertain parameters influencing the structural behaviour and yielding difference in numerical and experimental results. Hence parameter selection in model updating technique is the most important process. Of these, the uncertainties can be classified into two categories i.e. i) physical uncertainties and ii) numerical uncertainties. The physical uncertainties include boundary conditions, material properties, geometry and loadings. While the numerical uncertainties include conceptual modeling, mathematical modeling, numerical solutions and human mistakes. [8]. Moreover, selected parameter should be influential i.e. relatively small changes in the parameter values should give rise to significant changes in the model responses, while material properties are most influential [2]. Thus, current study is limited only to two of those material properties i.e. Moduli of Elasticity and Poissons Ratio.

1.5 Brief Methodology

In this study model updating for a simple prototype structure against impact loading is performed. The considered single storey, single bey prototype structure consists of 550mm high four aluminium columns fixed at steel base plate. A 500mm x 500mm x 5mm steel plate acts as a diaphram at the top. A calibrated hammer is used for the application of the impact load. A total of two accelerometers (i.e. one at hammer and the other at column top) are employed to record the impact load and structural response in terms of acceleration time history. For a comparative study, numerical analysis is performed using commericially available finite element modeling programme SAP2000 is used. Different parameters are considered for model updating based upon previous researches.

1.6 Research Significance and Practical Implementation

Structural designs are generally based on idealized material properties and boundary conditions. Standard material performances are determined by testing the materials in idealized conditions. Hence the response of the structures in real life differ from that of anticipated responses. Therefore the investigation of such parameters which significantly influence the change in structural response is the requirement of the time. This particular research covers the determination of impact of some of those influencing parameters. Consideration of impact of such parameters enables a designer to be more precise and realistic while designing the engineered structures. Hence more the safe and economic designs can be carried out.

1.7 Thesis Outline

There are six chapters in this thesis, which are as follows:

Chapter 1 consists of introduction section. It also consists of research motivation and problem statement, objective and scope of work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background, damages against impact loading, prototype structure, numerical modeling and model updating are explained.

Chapter 3 consists of experimental program. It contains background, experimental testing procedures and finite element modelling and model updating approach.

Chapter 4 consists of experimental evaluation. Results of experimental and numerical testing along with its analysis are covered in this section.

Chapter 5 comprise of further detailed discussion regarding obtained results.

Chapter 6 includes conclusion and recommendations. References are presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Structures are more prone to get damaged by impact loadings nowadays. Thus engineers are more concerned to ensure the structural safety against such loadings than ever before. An unfortunate increase in terrorist activities have also made this a point of concern for designers. A difference in experimental and analytical results has been observed by the researchers. Thus it encourages a dire need to study the precise behavior of structures under impact loading, and an updating technique. For such type of research prototype structure have been developed for investigation purposes. This chapter includes the literature review about damages caused to structures due to impact loadings, prototype structure used by the researchers in past, numerical modelling and model updating approach.

2.2 Damages of Structure due to Impact Loads

Impact loadings are one of the crucial loadings that create catastrophic failure of structures. It includes loads such as blast loadings nearby or inside structures, missile loadings and sudden impact of some falling object. A lot of structural progressive researches has been carried out against impact loading in recent decades.

Loss of lives and millions of dollars of property damage are the consequence following a targeted bomb attack. In or near a house, an explosion may cause catastrophic damage to the exterior and internal structural frames of the building [9]. In various parts of the world, such blasts against iconic and public buildings have become dangerous because of widespread terrorist activities [10]. It was reported the damage proxy map of the Beirut explosion on 4th of august 2020 [11].

In year 2020 a massive explosion occurred in the port area of Beirut, capital of Lebanon (Fig. 2.1) to have caused more than 200 peoples were killed and injured around 5000 others. The impact of blast damaged the homes as far as 10 kilometers (6 miles) away, and up to 300,000 people were left homeless by the explosion. Low-velocity impacts such as vehicle collision or rock fall are also a threat for structural safety. A shift in terrorist attack mode has been reported from static to penetrative attack using vehicles [12]. A blast attack to Islamabad Marriott Hotel in 2008 was reported to have caused 56 death causalities and 265 non-fatal injuries mainly due to structural damages [13]. In such cases structures not only need to have safety against explosions but also the vehicular collisions. Therefore, structural behavior during under the impact loading is an important issue to investigate.

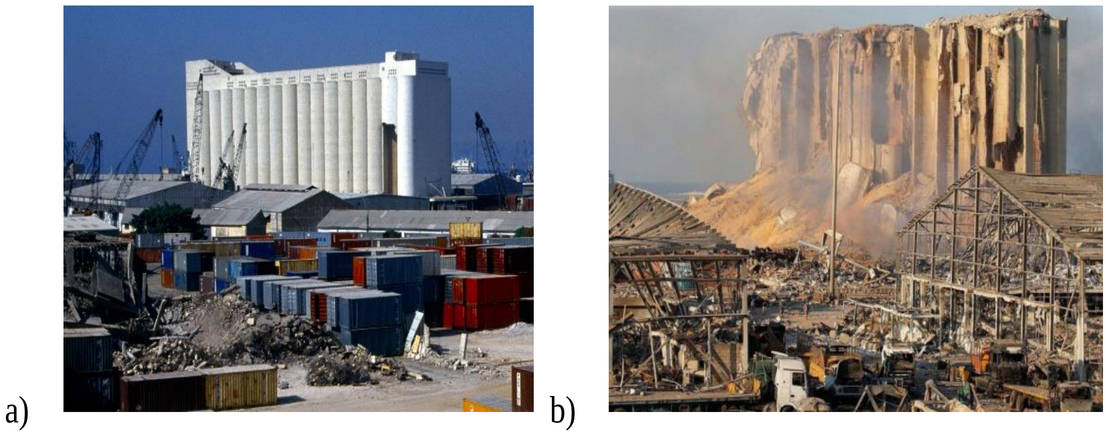

FIGURE 2.1: Beirut Port, a) Before explosion, and b) After explosion [33].

In the complicated ocean environment, offshore jacket platform are being used for the oil and gas exploration. Such offshore operations involve different types of loadings including wave, wind and ice loads. Whereas, beside all these such structure are also exposed to the unexpected and sudden application of loads such as impact of heavy object dropped off the height and vessel collision etc. Figure 2.2 shows offshore structure studied by Jim et al. These incidents may result in damaging the structures at different levels of severity including the reduction of load bearing capacity due to buckling or crooking of few members. Ultimately, affecting the safety of the complete structures. It was studied that the damages of an offshore structure caused by the impact of large barge during installation to assess the damage effects of the structure [14].

Figure 2.2: Offshore jacket platform, a) Studied structure [14], and b) Damaged offshore jacket structure due to impact load

Vehicle collisions into bridges have become more common in recent years, especially on major traffic routes and beltways. In reality, preventing or dealing with collisions between moving trucks and bridge structures is difficult: they obstruct the passage of other vehicles, obstruct traffic flow, and cause substantial damage to bridges and vehicles. In the United States, errant vehicles have collided with about 61 percent of overpass bridge piers [35], and vehicle crashes account for 15% of all bridge failures [36, 37]. Between 2001 and 2006, vehicles collided with approximately half of the urban overpass bridge piers in Beijing, China, accounting for 20% of total bridge damage caused by accidents [38]. As a result, automobile collisions are likely to damage or even kill metropolitan overpass bridge piers. Steel-plate composite (SC) walls are a relatively new construction material that is being considered as a viable alternative to RC walls due to benefits such as structural performance, resistance to impact and impulsive loading, and construction modularity, which could lead to time savings [39].

2.3 Prototype Structure and Simplifying Impact Load

For simulation of impact loads on structures, prototype structures have been used in the literature. These structures' responses are then exaggerated to reflect real-world structures. A simple model for computing real-structure response has been developed [2]. Four accelerometers were used to test the reaction of the prototype structure on a simple laboratory structure placed on a shake table. Reactive powder concrete (RPC) for ultra-high performance concrete (UHPC) was developed based on the formulated material [3]. Field blast testing was performed on columns made of these materials. After the detonation of a 35 kg trinitrotoluene explosion at a distance of 1.5m standoff, a column with micro steel fibre reinforcement "UHPC" retained 70% more loading capacity, while after the detonation of an 8 kg trinitrotoluene explosion at a distance of 1.5m standoff, only 40% of loading capacity was maintained.

The dynamic properties of prototype structures were assessed through hammer testing [20]. Three different structures are tested while natural frequencies, mode shapes and damping values were investigated in each of them. It was then concluded that the use of hammer for evaluating the as-built structural dynamic properties is successful for many civil engineering structures. Modern computer aided programs have now become a necessity for numerical analyses. However uncertainties are found in the properties of materials. A study was conducted on the updating algorithms for updating of models [8]. For the purpose, a simplified 2D prototype frame structure (Fig. 2.3) was considered to study under dynamic loadings. The observations and conclusions deduced from the study gave better results for unknown structural parameters using proposed updating technique.

Figure 2.3: Studied two-dimensional steel frame [8]

Several tests on a semi-rigid full-scale two storey steel frame were carried out to investigate the overall response of structure under the application of vertical load [15]. The structure consists of two bay frame having 5.0 m length, 3.0 width and 4.8 m height. Beam deflection, connection slip, side-sway and cracks were investigated in this study.

The combination of genetic algorithms and sequential niche technique is effective to find the global minimum for model updating of structural models. This combined technique is studied by Shabbir and Omenzetter [2] to explore the multiple minima that best describes the system for optimization of the responses. In the study a simple 3D laboratory frame (Fig. 2.4) was considered to apply the technique and obtain the experimental data.

Several experiments were conducted to investigate the self-centering RC frame structures using shake table [16]. A 1/2.5 scaled model was design and tested for different earthquake forces. The 7.0 m long and 6.0 m wide prototype was a 3-story reinforced concrete frame structure having self-centering frame system to resist lateral load. The prototype structure weighs about 12.61 ton with an added floor weight of 1.45 ton.

Calibration based on experimental results of steel beams was done for the deterioration parameters that are commonly used for non-linear simulation [24]. Effect of incorporation of random modelling parameters for deterioration variable

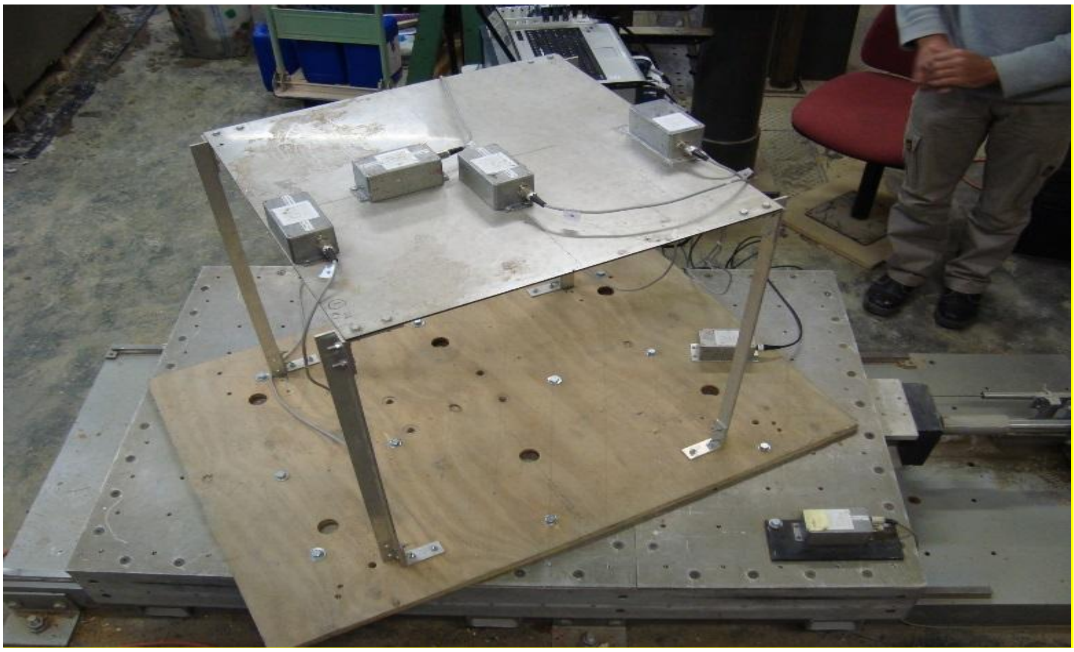

FIGURE 2.4: Three-dimensional steel studied frame structure [2]

in collapse fragility is focused. The study is performed on a five-storey prototype structure. It was concluded that the collapse capacity of steel structures is highly influenced by the strength modelling variables. Impact loading was simplified for the study of impact resistance of concrete walls having jute fibers as additives and Glass Fiber Reinforce Polymer bars as steel bars replacement [25]. Low and high impact loads are applied thorough a modified pendulum impact apparatus in laboratory. Basic dynamic properties of concrete slab are studied before and after initial cracking and ultimate failure. The local actions and damage of SC walls subjected to missile impact were evaluated in an experimental program. The findings of large-scale experiments have been presented elsewhere [40,41]. The outcome of missile impact experiments carried out on scaled-down specimens were presented that could be tested indoors in a structures laboratory [42].

2.4 Numerical Modelling for Structure Behavior

In the field of civil engineering finite element approach is being adopted primarily in the structure domain. Numerical modeling is also involved in other fields of civil engineering such as hydrological analyses and geotechnical analyses etc. The complex design and analysis of structures involve the solution of many difficult partial differential equations that govern the structural behavior.

To study the dynamic behavior of the structure, a full scale bridge model (Fig. 2.5) was created using SAP2000 [2]. For modelling of reinforced concrete plates subjected to blast loading, a 3D finite element model was proposed using LS-DYNA and SAP2000 [4]. The impact loading at the base of a prototype structure was used to investigate the dynamic response of a mortar-free interlocking structure [17].

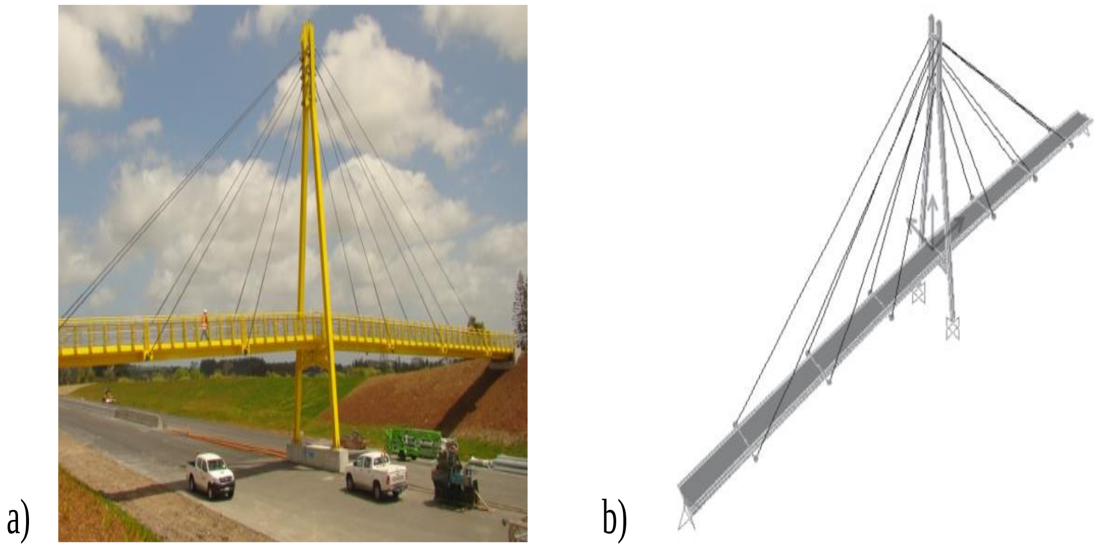

Figure 2.5: Structure studied by Shabbir and Omenzetter 2015, a) Full scale cable stayed bridge, and b) FE model of the bridge using SAP2000.

The dynamic response of offshore platform was analyzed including critical stresses and tabular joint deformations through numerical modelling to choose the most reasonable strengthening and repairing technique for the damaged platform [14]. The nonlinear seismic behavior of a six story building was observed which was severely damaged during Van (Turkey) earthquake in 2011 [18]. The study was done to investigate the reasons of structural failure. Qiandao prototype of submerged tunnel is studied against explosion and impact loadings [22]. The prototype is 3D modeled on ABAQUS software for performing the dynamic analyses. Stress strain states and displacements over time are studied. The influence of different materials such as concrete cover and steel plates is investigated both in prototype and numerical model.

Finite element model updating involves the solution of a constrained optimization problem, whose objective function is generally expressed as the discrepancy between experimental and numerical quantities, such as the structures natural frequencies and mode shapes. Due to inaccuracy in the model and a lack of knowledge in the measurements, ill-posedness or ill-conditioning can affect model updating formulations and lead to numerical problems. The probabilistic Bayesian approach is one of the most widely used approaches for quantifying uncertainties [50].

Jin et. al. [14] analyzed the dynamic response of offshore platform including critical stresses and tabular joint deformations through numerical modelling to choose the most reasonable strengthening and repairing technique for the damaged platform. avdar et al. [18] investigated the nonlinear seismic behavior of a six story building which was severely damaged during Van (Turkey) earthquake in 2011. The study was done to investigate the reasons of structural failure.

The modal analyses of the San Frediano bell tower and the Clock tower in Lucca, Italy, were performed using a simple method of FE model updating. The optimum values of Young's modulus and mass density of the materials are calculated in these works by fitting the data obtained by seismometric stations on the towers and running multiple simulations on a grid of feasible values [51-53].

Influence of pressure time history on structural response of corrugated plates under blast loading is studied [23]. Finite element code LS-DYNA is employed to analyze the structural response sensitivity of metallic plate to different parameters, subjected to experimental data. It was concluded that the complex pressure history can be reduced to simplified pulse for structural analysis.

Shabbir and Omenzetter [2] prepared the full scale bridge model using SAP2000 to study the dynamic behavior of structure. Xu and Lu [4] was proposed a 3D nite element model by using LS-DYNA and SAP2000 for modelling of reinforced concrete plates subjected to blast loading. Ali et al. [17] studied the dynamic response of mortar-free interlocking structure by applying the impact loading at base of prototype structure.

The impact force profile was investigated by drop weight impact method on RC beams. LS-DYNA is used for the numerical study of effects of global stiffness by changing boundary conditions [26]. Empirical equations are developed to validate the results of numerical model and were found to be in good agreement.

It can be concluded from the above discussion that finite element modelling and analysis approach is being adopted by the engineering community for design and research purposes. Different finite element modelling and analysis programs are available while SAP2000 and ETABS are being commonly used. Hence, such a study can be made for this specific project.

2.5 Model Updating Parameter to be Consider for Updating

Techniques of model updating is about updating a finite element model of a structure so that it can assume higher accuracy of structure dynamics. As shown in Table-2.1, quite a few methods of structural model updating have been implemented and this subject is currently under research in different sectors. Most of these studies focused on approaches such as optimal matrix updating, parameter estimation-based parameter estimation based on sensitivity, Eigen-structure assignment algorithms, and neural-network updating methods.

Model updating with finite elements (FE) is a method for calibrating a structure's FE model to match numerical and experimental performance [43,44]. It was first used in the 1980s and has since proven to be extremely useful in the design, study, and maintenance of aerospace, mechanical, and civil engineering structures [45,46]. Model updating methods, in combination with vibration measurements, are used in structural mechanics to determine unknown components such as material properties, constraints, and so on. The revised FE model can then be used to make accurate predictions about the structure's dynamic behaviour under time-dependent loads. Another major use of model up is in the area of research and development. Damage detection is another significant application of model updating in the context of structural health monitoring. A further important application of model updating, within the framework of structural health monitoring, is damage detection [47,48].

Model updating on finite element models is presented using a novel approach. The method is especially well suited to building modal studies, in which the lowest frequencies, as determined by sensors and device recognition techniques, must be matched to the numerical frequencies predicted by the model. This is accomplished by optimising certain unknown material parameters (such as mass density and Young's modulus) and/or boundary conditions, which are also only understood roughly [49].

The selection of model updating parameters plays an important part in successful updating process. The selected parameters should be realistically controllable to yield best possible results and make close relevance between numerical and experimental test data [30].

According to Brownjohn and Xia [27] the selection of model updating parameters plays an important part in successful updating process. The selected parameters should be realistically controllable to yield best possible results and make close relevance between numerical and experimental test data.

The sensitivity-based methods are widely used methods for FE model updating due to their good performance to reconstruct the measured response quantities, such as natural frequencies and mode shapes, etc. An improved sensitivity-based parameter updating approach was proposed [6]. Response surface methods for finite element modelling was used by Marwala. Genetic algorithms calculation was used for updating parameters of the finite element modelling by optimizing the surface response equation. The parameter selection procedure for model updating is the most significant step of the discrepancy minimization. A study was conducted to compare the parameter selection techniques for model updating [21].

The generic element matrices technique was found helping in parameter selection. It was also concluded that the adjustment in physical parameters is not the only way to produce the model consistent with test data. Hence finite element zero entries might also be significant in this regard.

The selection of model updating parameters [27], is critical to a successful updating method. To achieve the best results and ensure close correlation between numerical and experimental test data, the parameters chosen should be realistically controllable.

A statistical algorithm for the detection of structural damage was proposed using MSE sensitivity for the damage detection process based on ambient vibration measurements, where the only data available is shapes in operational mode [7]. Yan et al. [7] proposed a statistical algorithm for the detection of structural damage using MSE sensitivity for the damage detection process based on ambient vibration measurements, where the only data available is shapes in operational mode. Updating parameters are the most important in finite element model. The consideration of these factors is not normally taken into account in regular model construction [8].

Table 2.1: Model updating parameters and percentage improvement by other researchers

Model Description	Emphasis	Updating Procedure	—	—	Percentage Improvement	References
		Description	Before	After		
Finite Element Model of Column	Model updating is implemented by the proposed algorithm to get the uncertain parameters.	• Modulus of Elasticity • Poisons Ratio • Connection Rigidity	2.04256E11 N/m2 0.33 95,000 Nm/rad	2.04702E11 N/m2 0.33 94,870.66 Nm/rad	90%	Basaga et al. (2011).
Simple Model For Computing Response of Real Structure	Model updating methods, especially the sensitivity approach is used. The presented methods allow the processing of time and frequency domain data.	• Modulus of Elasticity • Stiffness “K”	70,000 MPa 6	72,000 MPa 4	70%	Fritzen et al. (1998)

2.6 Novelty of Current Work

Model updating approach is being employed as a part of validating and verification process of the numerical models. The structural responses obtained from these numerical models are often called into question when found contrary to that of experimental test results. Hence this very technique is considered as a correction and then verification tool for the numerical models by processing records of dynamic response from test structures.

To the best of authors knowledge the investigation of a 3D structure with the purpose of model updating under the impact load particularly has not been conducted yet. Hence the current study calls-in the researchers to pursue the study related to this very issue to overcome the problems in structural stability. Thus, this study presents significantly remarkable results regarding the structural response under the application of impact load and requires to be studied in further depth for better solution.

2.7 Summary

Structural safety is the primary aim of all structural design engineers. Therefore, they always look forward to minimize the threats to the safety of structure. To overcome the pertaining difference between numerical and analytical behavior of structure under the impact loads, model updating approach is studied. Prototype structures are considered on small-scale in laboratory to investigate the behavior of structure under the impact load. To start with, few of the parameters among several studied by the researchers are considered. The following sections of this study consists of detail discussion about model updating of a simple structure under impact loading.

Chapter 3

Experimental Program

3.1 Background

Modern techniques are now being employed to design the structures. Computer aided analysis and design has now become a common practice of structural design engineers. Designers while simplifying the real world problems with the help of computer programs to overlook certain important parameters causing a significant difference between actual and analytical response of the structure. To overcome this particular problem model updating approach is being studied by the researchers. In this study model updating for a single storey simple 3D structure under impact loading is done. The chapter under sight discusses the detailed methodology adopted for this particular study.

3.2 Experimental Test Setup

3.2.1 Experimental Test Setup

The simple 3D prototype structure is shown in Fig.3.1 (a), whereas Fig.3.1 (b) shows the schematic diagram of prototype structure considered in this study. The prototype structure is the same as the one used by Shabbir and Omenzetter in their research [2]. In order to have top displacement in column against small magnitude of impact load, aluminum columns are being used instead of steel columns. The structure is made of a steel top plate supported on four columns made of aluminium angles. It has a height of 550 mm. The steel plate is 500 mm x 500 mm and has a thickness of 5 mm. The aluminium angles have dimensions of 30mm x 30 mm with a thickness of 3 mm. The columns are attached to the steel plate at the top and to a bottom steel plate with L-shaped aluminium brackets having a width of 30 mm, thickness of 4.5 mm and length of 75 mm. Bolts are used to connect each bracket with the top steel plate, bottom steel plate and an aluminium angle. A total of two accelerometers were used to measure the response of structure under impact loading. The impact force P is applied at the bottom of column with the help of hammer. One accelerometers are mounted at the top of column to measure the response, whereas the second accelerometer was mounted on hammer to measure the acceleration of applied impact force. The result of accelerometer is recorded in MATLAB software in terms of acceleration-time history notated as $\ddot{u}_h$, $\ddot{u}_1$, and d$\ddot{u}_2$.

a.

b.

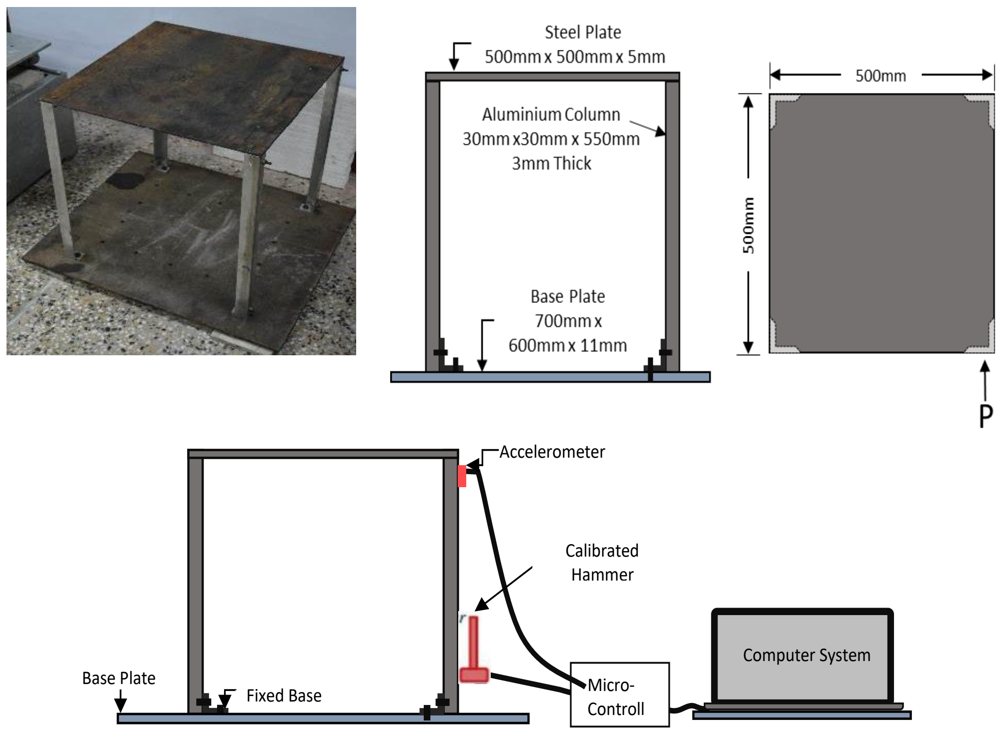

FIGURE 3.1: Experimental test setup, a. prototype structure, b. Instrumentation.

3.2.2 Impact Loading

Impact loading is always a challenging type of loading for the designers to cater for in the structural designs. The uncertainty of its magnitude is one of the major reason. Impact load give a sudden rise to the rate of strain hence activate inertia and consequently influence the strength, stiffness, ductility and failure mode of the structure. The replication of impact load on large scale for the investigation of its effects on structures is not possible. Hence such loads are simplified in different manners. Therefore, in this study the application of impact load was carried out through a calibrated hammer shown in Fig.3.2.

FIGURE 3.2: Calibrated hammer used for the application of impact load

Since the load application process was manual, the magnitude of impacts was not constant. Hence three different levels i.e. low, medium and high impact loads were defined covering the ranges of 0 N to 1 N, 1 N to 2 N and higher respectively. The peak accelerations were than normalized for the comparison results under varying magnitudes of impact loading.

3.3 Finite Element Model and Updating Approach

3.3.1 FE Model

The numerical modelling approach is being used since decades to understand the structural behavior. In order to simulate the dynamic behavior of single bay single storey 3D frame structure under the application of impact load for a relative comparison between numerical and actual response, numerical modelling is done using SAP2000 program. Figure 3.3 shows the finite element model developed using SAP2000.

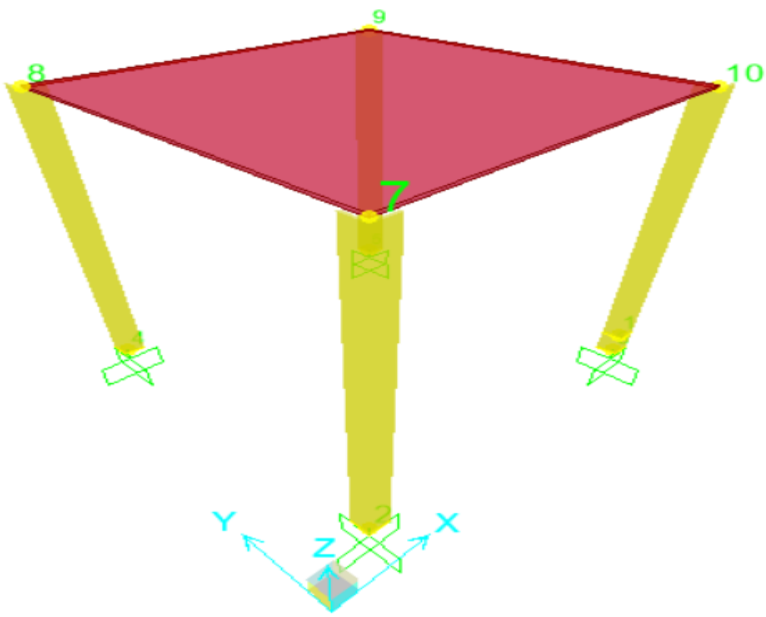

FIGURE 3.3: Finite element model of 3D frame structure under study

The finite element model is created using the same materials and geometric properties as the prototype structure in a computer programme SAP 2000. Material properties used in the numerical model are described in Table 3.1. The columns are modelled with steel frame elements and the top plate as a slab element having a rigid joint condition. Fixed supports are introduced at each column end.

The application of impact load in numerical model was based on the actual data set recorded using accelerometers while conducting the experimental testing. All

TABLE 3.1: Material properties used in numerical model before model updating

Sr. No.	Parameter	Aluminium Columns	Steel Top Plate
1	Size (mm)	30 x 30 x 3	500 x 500 x 5
2	Modulus of Elasticity, E (GPa)	68.9	200
3	Poissons Ratio, v	0.33	0.3

the three magnitudes i.e. low, medium and high as discussed earlier in section 3.2.2. were applied for relative analysis of structural behavior under respective loadings. The point of application in numerical model was defined by assigning a node at one of the column following the same configuration considered while experimental program.

3.3.2 Model Updating

Designers now a days are very much relying upon the computer aided analysis and design of engineering structures. The structural behavior simulated by such computer programs have been observed to have differences relative to that of real life structures due to being more theoretical. Several parameters are involved in such irregularities in structural behavior as studied by many of the researchers. To overcome such differences model updating technique is being studied by the researchers considering different parameters. Based on the methodology proposed researchers [8], a pilot study of 3D single storey structure under impact loading is conducted to minimize differences between numerical and experimental response of structure.

3.3.2.1 Updated Parameters

To achieve the desired results, consideration of parameters is one of the most important factor. Among many of the parameters, Moduli of Elasticity and Poisons Ratio are considered in current study based upon the findings of Basaga et. al.

[8]. These two parameters have been updated on hit and trial basis to minimize the differences.

3.4 Summary

This chapter includes the detailed discussion regarding experimental and numerical techniques employed in this particular study. The prototype 3D single bay single story structure was tested under the application of impact loading of three different magnitudes. The method to record the respective behavior of the structure for a comparative analysis is also discussed. Moreover the model updating technique including the parameters considered in this very study are also discussed.

Chapter 4

Experimental Evaluation

4.1 Background

Experimental procedures were discussed in the previous chapter in detail. This chapter includes the experimental evaluation of recorded data. Data record and analysis is done using different computer programs such as MATLAB, Seismosignal, SAP2000 and MS Excel. Structural response recorded experimentally against three different magnitudes of impact load i.e. low, medium and high is then compared with the response obtained from the numerical model. Model updating technique is then employed to minimize the observed differences.

4.2 Structural Response against Impact Loading

4.2.1 Experimental Analysis

A single bay single storey 3D structure was tested against impact loading of three different magnitudes i.e. low, medium and high for a comparative analysis of dynamic characteristics. Since the application of impact load was done manually through a calibrated hammer, the consideration of levels of applied impact load is based on hit and trial method as done by Ali et. al. [17]. The experimental response of structure was recorded using accelerometer placed at the top of one of the four columns in terms of acceleration-time histories. The peak acceleration at column top ($\ddot{u}_t$) against impact loads are shown in Table 4.1.

TABLE 4.1: Applied impact load at column bottom (P_b) and peak acceleration at column top (u_t)

Test No.	Low	Low	Medium	Medium	High	High
	Pb (kN)	ut (g)	Pb (kN)	ut (g)	Pb (kN)	ut (g)
1	0.83	0.66	1.85	0.56	2.11	1.25
2	0.93	0.58	1.6	0.88	2.41	1.12
3	0.82	0.79	1.57	0.85	2.57	1.47
4	0.75	0.57	1.41	0.76	2.42	1.35
5	0.55	0.5	1.52	0.87	2.28	1.16
Average	0.776±0.14	0.62±0.11	1.59±0.16	0.784±0.13	2.358±0.17	1.27±0.14

Figure 4.1 shows the correlation between the induced acceleration and applied impact force. It is evident from the figure that the levels of impact force considered for the study generate anticipated results having close relevance with respect to magnitude.

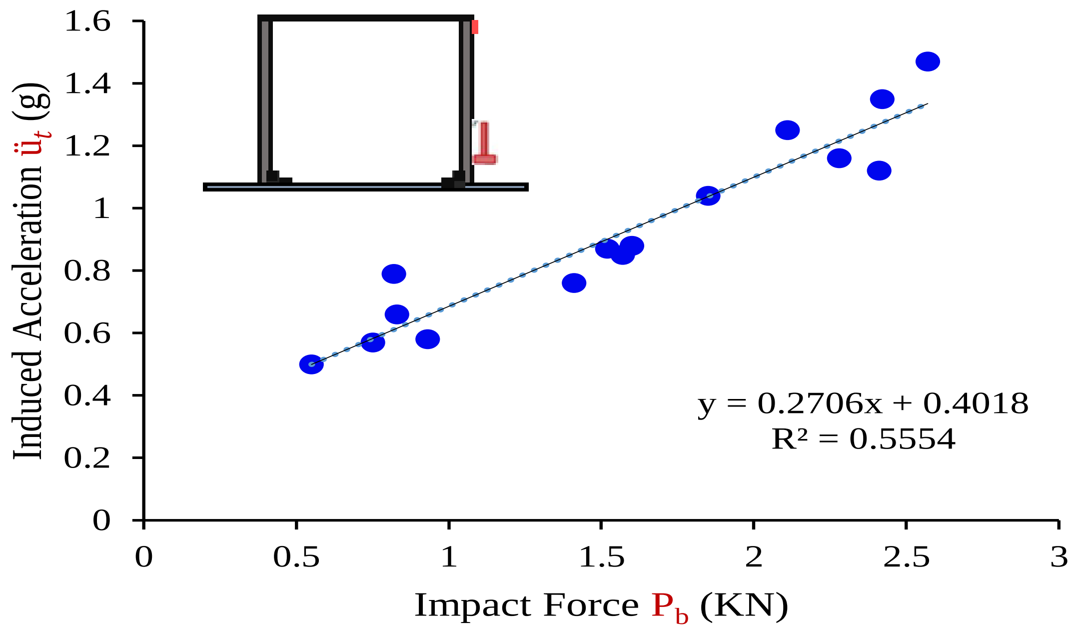

FIGURE 4.1: Correlation between induced acceleration and impact force

The typical structural response recorded experimentally in terms of acceleration time history close to the average values for each of the impact magnitude i.e. low, medium and high is shown in the Fig. 4.2. It can be seen that the peak acceleration recorded at column top increased with the increase in impact magnitude. A similar response is observed in all five iterations against each impact magnitude and is shown in Annexure-A.

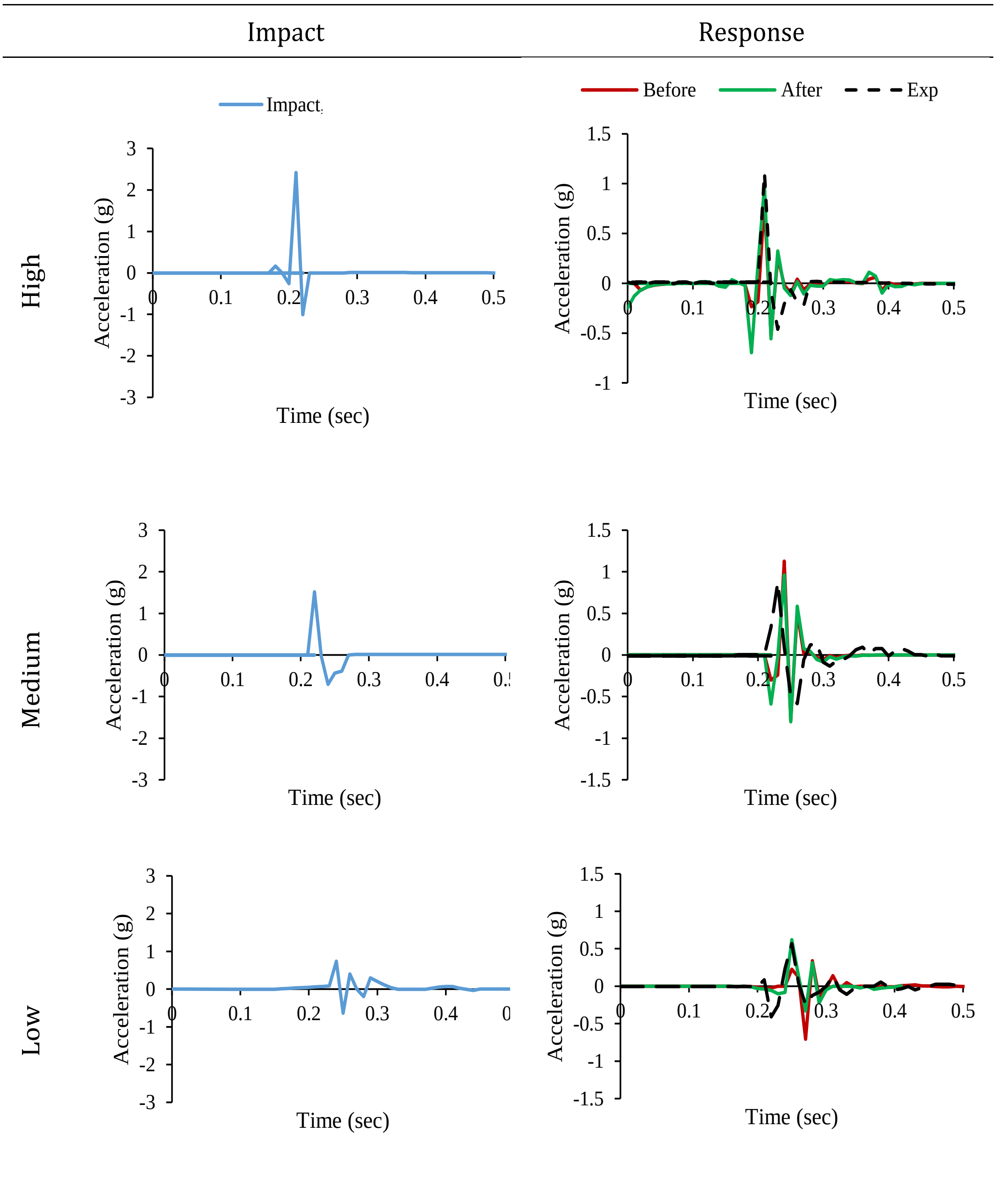

FIGURE 4.2: Low, Medium and High Impact and Response

4.2.2 Numerical Analysis

To conduct a comparative analysis between experimental and numerical response of structure for the purpose of minimization of differences through model updating approach, experimental record is fed to the SAP2000. A similar trend in response was observed against each impact load but with difference in its numerical values. Considering the Poissons Ratio and Moduli of Elasticity as the only updating parameters the hit and trial method of model updating approach was employed purposefully to minimize the irregularities. The aforementioned parameters were adjusted realistically and the respective responses against each of the experimentally recorded impact load were observed.

4.2.2.1 Structural Response without Model Updating

Table 4.2 shows the numerical response in terms of peak acceleration at column top against low, medium and high magnitudes of impact loads along with a relative percentage difference from experimental response.

Table 4.2: Numerical peak accelerations without model updating

	Peak Accelerations (g)					
	Numerical value without model updating			Percentage Difference (%)*		
Test No.	Low	Medium	High	Low	Medium	High
1	0.522	0.749	0.771	21.4	33.9	38.3
2	0.718	0.632	0.811	26.5	28.2	36.6
3	1.016	0.616	1.004	28.6	27.5	31.7
4	0.707	0.989	1.793	24.1	30.1	32.7
5	0.632	1.127	0.786	27.1	29.5	32.2
Average	0.719±0.18	0.822±0.22	1.033±0.43	25.54±2.82	29.84±2.49	34.335±2.94
*[(Exp-	Num)/Exp]x100					

A difference in experimental and numerical peak acceleration of about 25-35% can be seen to have been observed. Moreover an increase in percentage difference is observed with the increase in magnitude of impact load. The peak top accelerations recorded experimentally show that it does not have any direct relation with increase or decrease in magnitude of impact load. Rather the location of the impact load is of significance. Hence the consideration of idealized loading condition does not yield the actual response of structure. Therefore the differences in the numerical and actual structural response arise. These differences raise a serious concern regarding structural designs as numerous reasons are involved in it. Particularly the ideal consideration of material properties during numerical analysis.

4.2.2.2 Structural Response with Model Updating

Keeping in view the fact discussed earlier and the previous researches, few parameters were updated to minimize the differences. Table 4.3 shows the numerical peak accelerations after model updating.

TABLE 4.3: Numerical peak accelerations with model updating

	Peak Accelerations (g)					
	Numerical value with model updating			Percentage Difference (%)*		
Test/ Impact Intensity	Low	Medium	High	Low	Medium	High
1	0.719	0.624	1.105	8.2	11.6	11.5
2	0.614	0.801	0.981	8.1	9.09	12.9
3	0.713	0.766	1.688	9.7	9.88	14.8
4	0.621	0.686	1.501	8.9	9.72	11.0
5	0.534	0.961	1.020	7.4	10.5	12.1
Average	0.643±0.07	0.767±0.12	1.259±0.31	8.46±0.87	10.158±0.94	12.46±1.48
*[(Exp-	Num)/Exp]x100					

The updating technique employed yield impressive results and the peak accelerations can be seen to have improved significantly. The improvement showed an increasing trend with increase in magnitude i.e. higher percentage improvement is observed in high impact as compared to low impact. The reason for which is higher effect of material uncertainties against higher impact.

4.3 Summary

The consideration of design parameters plays a significant role in the process of structure design. Difference in structural response as anticipated in comparison with the actual raises a big question mark for the structural safety. Similar results were observed during the current study in which a difference of about 25-35% was recorded and was minimized through modern model updating approach upto 12%. The study opens doors for further in detail analysis to overcome the differences in numerical and actual response of structure.

Chapter 5

Discussion

5.1 Background

Finite element analysis is an essential tool used for structural design under dynamic and static loadings. However, a lot of uncertainties are found in the structural properties. For this reason, differences in experimental and numerical responses are observed. Such differences in experimental and numerical results of structure under the application of impact load requires optimization for a safe and economical design. Experimental evaluation of the current study in this regard is presented in the previous chapter in detail. This chapter includes the interpretation and discussion regarding the outcomes of the experimental evaluation. Percentage differences in results and percentage improvement before and after model updating is discussed respectively in detail.

5.2 Difference in Experimental and Numerical Results

Several parameters can be considered for a comparative study, but current study focuses only upon the differences found in the induced accelerations in column due to the application of impact load. The subsequent sections discuss such differences observed during the experimental program. Model updating technique is then employed in an effort of minimization focusing to make maximum relevance in both the numerical and experimental responses of structure. Furthermore, the outcome of current study in light of experimental evaluation is also presented.

5.2.1 Percentage Difference

The percentage of differences between the experimental and numerical results is tabulated in Table 5.1. It is noted that the significant difference in peak induced accelerations against all the three impact magnitudes occurred. An average percentage difference of almost 25%, 30% and 35% is observed against low, medium and high impact loads respectively.

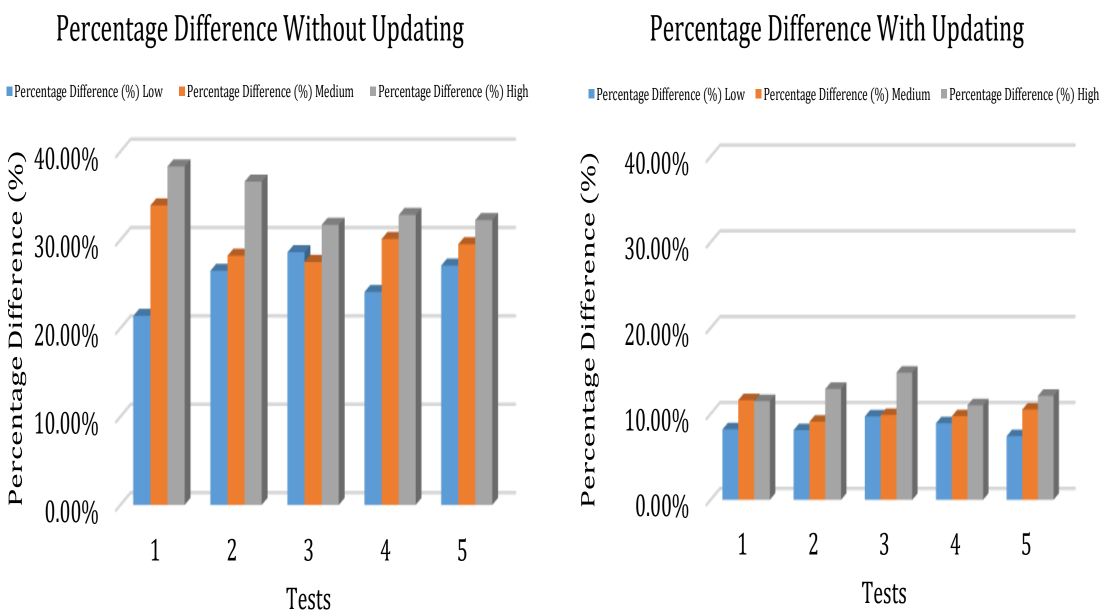

FIGURE 5.1: Percentage difference without and with model updating

Such significant difference cannot be neglected while designing the structures and can be a severe potential hazard for structural safety. Such results ring an alarm for the design community and signifies the need to study the subject in further detail. Furthermore, the consideration of idealized material properties in the design process also need improvement as these may differ in the reality.

5.2.2 Percentage Improvement

In view of the discussion above, model updating technique was employed and a significant improvement in numerical peak induced accelerations was observed comparative to the experimental peak induced accelerations. Table 5.1 shows the percentage improvements against all the three magnitudes.

Table 5.1: Percentage improvement with model updating

	Percentage Improvement (%)		
Sr. No.	Low	Medium	High
1	13.2	22.3	28.1
2	18.3	19.0	23.7
3	18.8	17.6	16.7
4	15.1	20.4	21.7
5	19.7	18.9	20.1
Average	17.02±2.75	19.64±1.78	22.06±4.23

It can be seen that the peak induced accelerations improved significantly after the updating certain parameters. An average improvement of almost 17%, 19% and 22% can be seen to have occurred due to change in particular parameters.

Table 5.2 tabulates the percentage changed made in the material properties for both the columns and top plate of studied prototype structure. It can be seen a nominal change in material properties yields up to 22% of improvement in structural response. which in other words highlights the significance of realistic consideration of material properties in design to achieve the better structural stability.

Figure 5.2 shows a similar increasing trend in improvement with respect to the increase in impact magnitude as discussed earlier in the percentage difference. The peak induced accelerations improved dramatically after those parameters were modified, as can be shown. Increasing trend in improvement with respect to the increase in impact magnitude is observed. This might be because of frequency

TABLE 5.2: Actual Change in Material Properties after Model Updating

Sr. No.		Aluminium			Steel	
E	–	69	–	–	200	
	4.50%	65.84	72.05021	3.50%	193	207
V	–	0.33	–	–	0.30	
	3.50%	0.32	0.34155	3.00%	0.291	0.309

match. The fact reveals that the higher the magnitude of the impact load the more will be the difference, which certainly is a threat for structural stability.

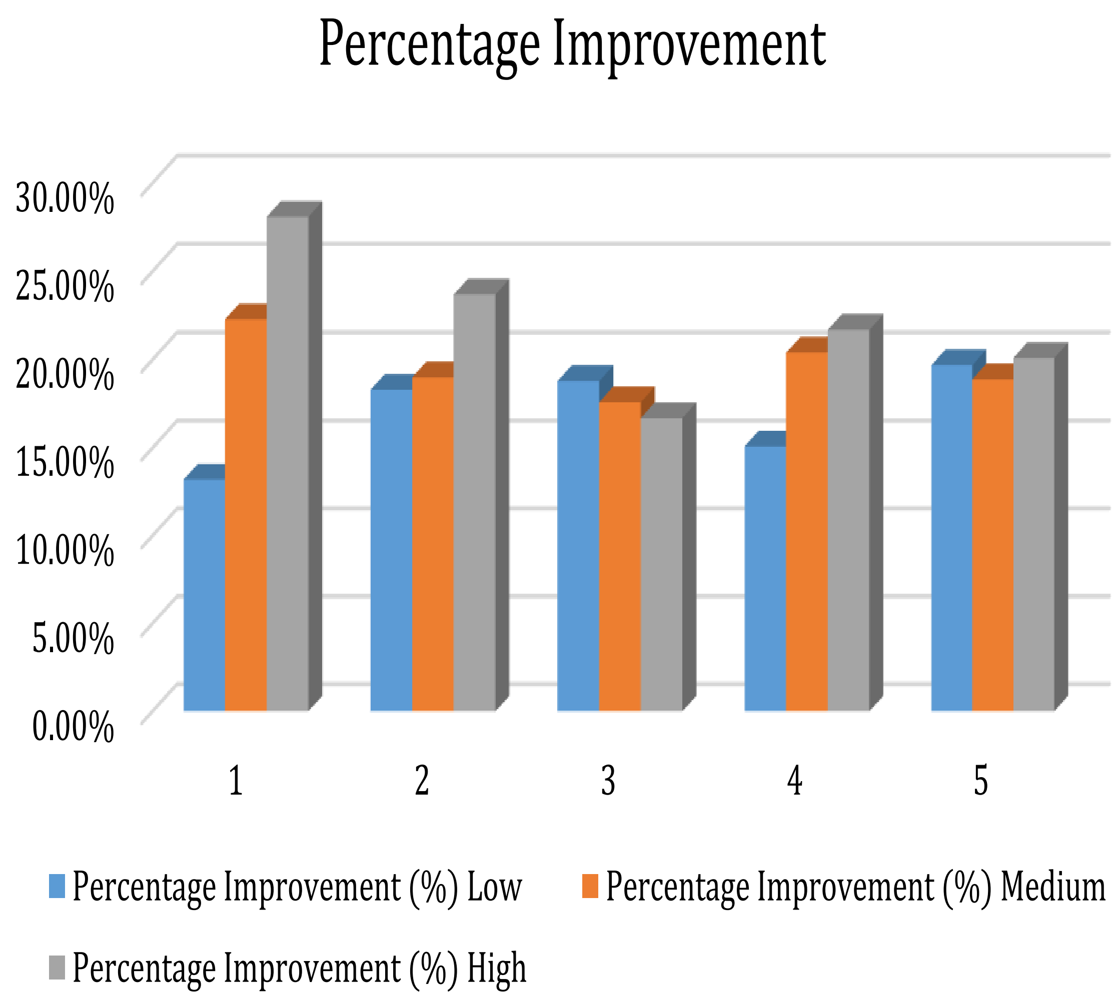

FIGURE 5.2: Percentage improvement in peak induced acceleration after model updating

5.3 Outcome of Study with Respect to Practical Requirements

In view of the above detailed analysis and discussion, it is evident that consideration of idealized material properties and design parameters in the design phase while the use of materials with different properties at site, may cause a significant difference in structural response. Such difference raise serious concern regarding structural stability. Following are the outcomes of study with respect to practical requirements:

- Considering the differences, improvement is required both in design and execution phase of construction.
- Anticipation of more realistic behaviour of structure such as load transfer mechanisms may lead to relevance in both numerical and experimental responses.
- Poor workmanship and execution practices also alter the material properties such as tightening of bolts above limits and excessive use of heat while welding etc.
- Designers need to have sound knowledge of material properties available in the region for a more realistic consideration in design.
- The selection of material has to be payed serious attention in coordination with the designer to procure material having properties nearest to those considered in the design.
- Change in serviceability of structure may cause serious impact on designed strength of structure which may lead to failure in structures.
- The most influential parameters like Moduli of Elasticity and Poissons Ratio should be studied in detail.

5.4 Summary

The detailed discussion regarding percentage differences and percentage improvements in peak induced accelerations against low, medium and high magnitudes of impact loads is made in this chapter. Significant improvement in the responses has been observed through modification of material properties. Further in the chapter, outcomes of the study related to the practical requirements are presented. The consideration of those outcomes discussed here but not limited to them may lead to better results. The discussion made in the chapter signifies the in-depth study of the structural behavior against impact loading's for better understanding and minimization of possible differences.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In current work, model updating technique is employed to minimize the differences between the numerical and experimental response of structure under the application of the impact load. For the purpose a combination of numerical models have been analyzed to get the realistic results near to experimental. Numerical responses have been recorded against three different magnitudes of impact load i.e. low medium and high. The results are then compared with the respective experimental results to analyze the differences. Employing the modern model updating technique, specific material properties are modified based on the previous studies and the obtained results are then compared with the numerical results without model updating as well as experimental results. Following conclusions have been drawn from the current study:

- Modulus of elasticity and Poissons Ratio of material are most effective in model updating as compared to other parameters.
- Peak acceleration responses of numerical and experimental result are taken as comparison.

- It is noted that the difference in the numerical and experimental results is due to uncertain parameters of structure.
- An average improvement of almost 17%, 19% and 22% can be seen to have occurred due to change in particular parameters.
- The nominal change in material properties yield up to 22% of improvement which highlights the significance of these parameters in structural design.
- Impressive results in the form of improvement in peak acceleration are obtained which encourages further in-depth study.
- The improvement in peak acceleration yielded significant results, prompting more in-depth investigation.
- The obtained favorable results in current study suggest indepth investigation in future.

6.2 Future Work

This study has shown impressive results in terms of model updating for a simple structure against impact loading.

- The study should be extended to the investigation of more realistic multi-story structural models such as RCC structures.
- Further precise study should be conducted considering more accurate results by getting the response of other structural members simultaneously, other than the member under the application of impact loading.
- Effect of other parameters such as boundary conditions and other material properties should be investigated for a better understanding.

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Annexure A

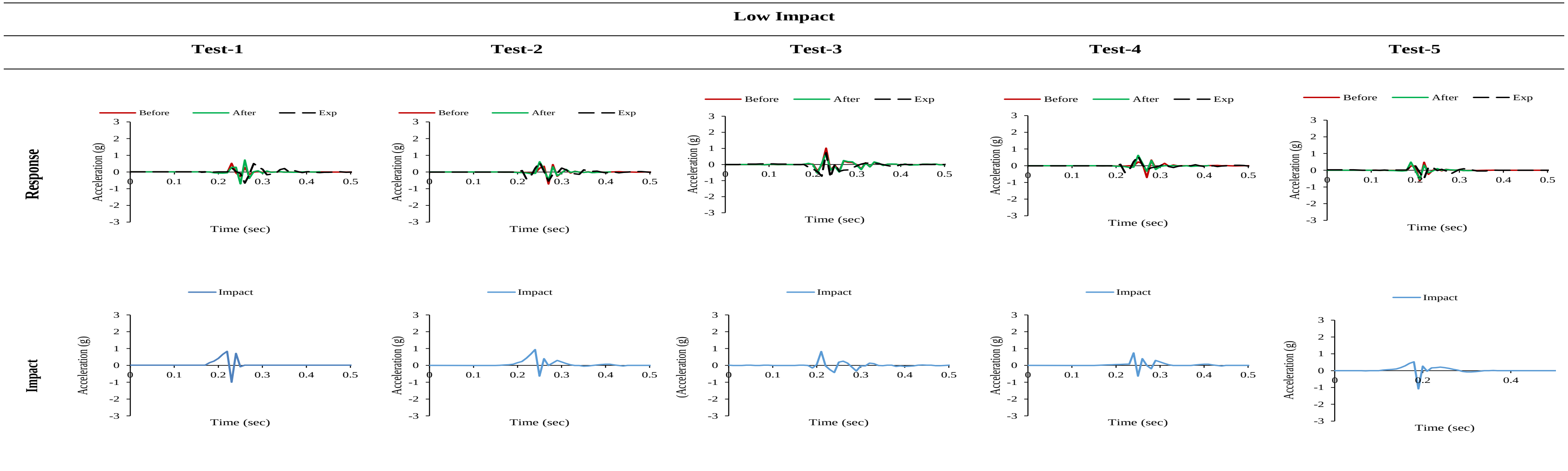

Figure A.1: Peak induced accelerations at column top under the impact of Low magnitude

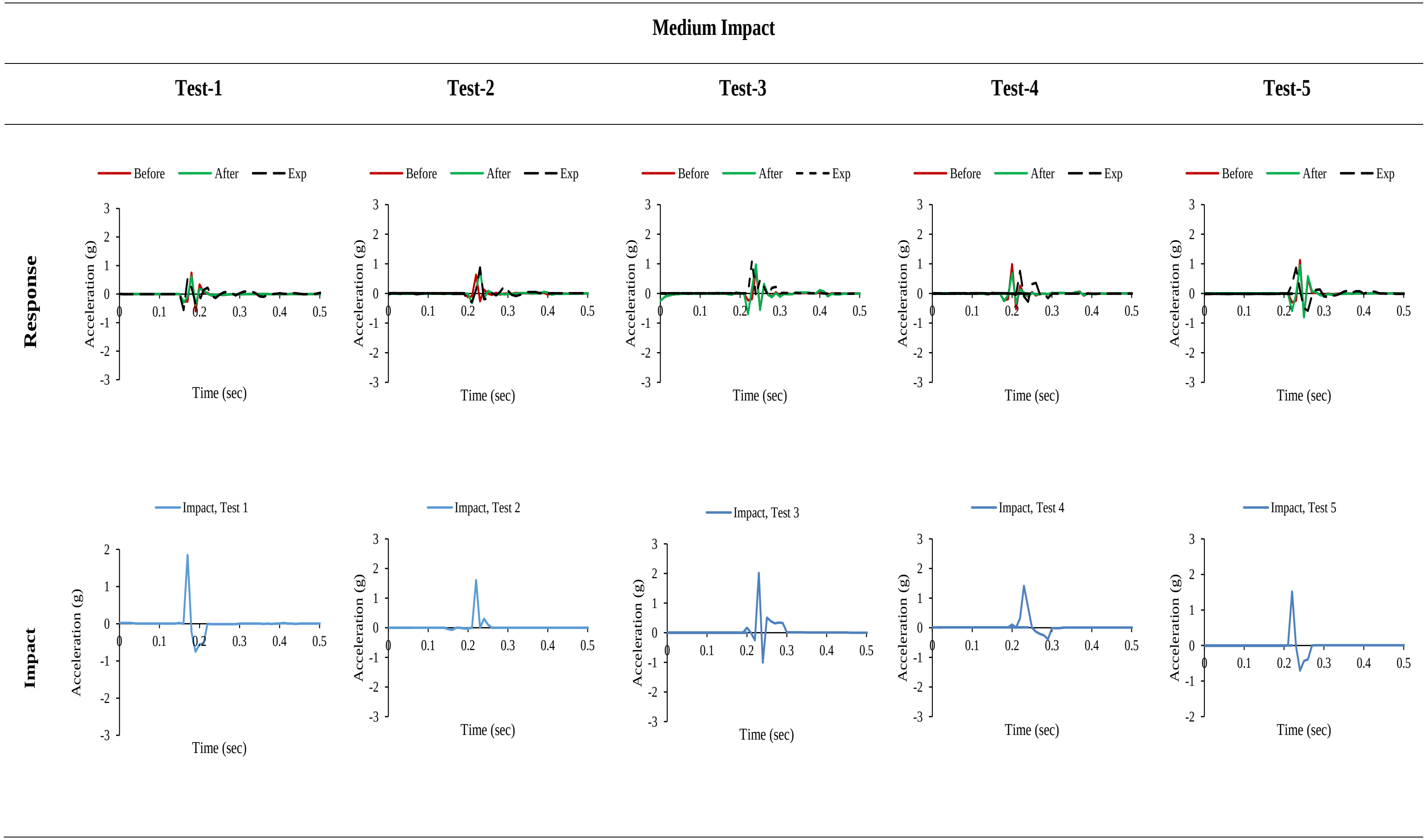

FIGURE A.2: Peak induced accelerations at column top under the impact of Medium magnitude

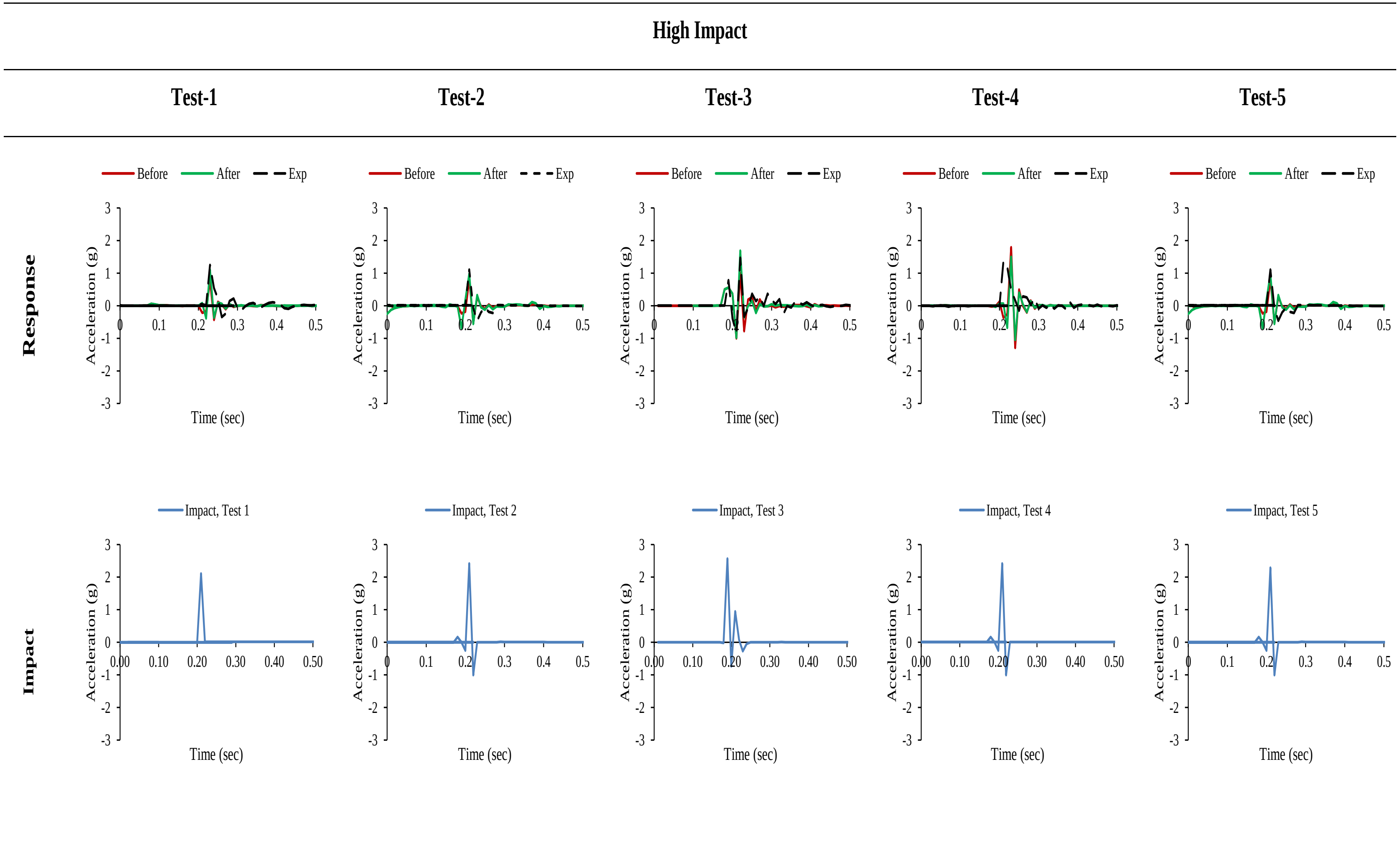

FIGURE A.3: Peak induced accelerations at column top under the impact of High magnitude