Progressive Collapse Assessment of Multi-storeyed Building

A DISSERTATION

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OF

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IN

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Submitted by

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CANDIDATE'S DECLARATION

I, MD OSAID ARSHAD, Roll No: 2K19/STE/15 student of M.Tech, Civil Engineering Department, hereby declare that the project Dissertation titled "Progressive Collapse Assessment of Multi-storeyed Building" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the Degree of Master of Technology in Structural Engineering is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any other degree, Diploma Associateship, fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "Progressive Collapse Assessment of Multi-storeyed Building", which is submitted by Md Osaid Arshad, Roll No. 2K19/STE/15 Civil Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

The issue of progressive collapse has been trending since it's connected with uncertainties that can make it difficult to accurately assess a structure's safety. The purpose of the current is to perform bibliometric analysis along with literature review of progressive collapse and execute progressive collapse analysis of a seven-storey RC building in SAP2000 and study the influence of different parameters of the building.

In this study nonlinear dynamic analysis coupled with response surface methodology (RSM) is employed to investigate progressive collapse of a seven-storey RC building. For nonlinear dynamic approach of progressive collapse, structural analysis software SAP2000 is used. In response surface, Box–Behnken design is employed to analyse the progressive collapse of the structure with three positions of column elimination i.e. corner, middle and penultimate position.

The current study considered three independent input variables namely grade of concrete, length and depth of beam with three levels and deflection of beam is taken as a response. Based on the ANOVA results, all three input parameters have substantial impact on the response in each of the three positions of column elimination. In each case RSM fits quadratic model for deflection of beam with confidence interval of 95%. The response calculated using the generated model is found to be quite close to the actual readings. The main effects plots are not horizontal line which describes the significance of individual factors with different levels on the response. Results shows that with the increase in the values of grade of concrete and depth of beam, the vertical

deflection of the upper node of column removal point decreases whereas increase in beam length increases the deflection. The interaction effect of different factors, grade of concrete versus beams length and beam depth versus beam length, is significant in corner column elimination. But in middle column elimination case, the interaction effect of beam length versus depth is close to significant while no interaction effects are found significant in penultimate column removal case. The values of grade of concrete and beam depth should be in the higher range and beam length should be in the lower range to get the optimal response. It also covers limitations and future research of the current study.

ACKNOWLEDGEMENT

I gratefully appreciate my supervisor **Dr. Shilpa Pal** for her continuous guidance, support, advice and attention to the details during the development of my project explained here in the dissertation. I especially thank her for her patience and tolerance in one of the toughest period of my life. I would like to extend my thank to co-supervisor **Dr. Mohammad Umair** for his contributions in the project and humble behaviour towards me. I express my heartfelt thanks to **Prof. Vijay K. Minocha**, Head of Department, Civil Engineering. I also expresses my regards to Ministry of Human Resources and Development (MHRD), Govt. of India who have provided me post graduate scholarship through the academic session to complete my course. I extend my gratitude to **Delhi Technological University** for giving me this opportunity.

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MD OSAID ARSHAD

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LIST OF ABREVIATIONS

AEM	Applied Energy Method
ANOVA	Analysis of Variance
BBD	Box–Behnken Design
CCD	Central Composite Design
df	Degree of Freedom
DoD	Department of Defence
FEM	Finite Element Method
F-value	F Distribution Value
GSA	U.S. General Services Administration
KCN	Keywords Co-Occurrence Network
p-value	Probability Getting Test Result.
PDEM	Probability Density Evolution Method
RC	Reinforced Concrete
RSM	Response surface Methodology
R^2	Coefficient of Determination
SDC	Seismic Design Category
α	Significance Level

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Over the last few decades progressive collapse has been a hot topic for structural engineers and researchers. It earned the attention after Ronan Point building collapse due to an explosion caused by gas leakage in a kitchen and accelerated the research after terrorist attack on World Trade Centre towers in 2001.

Progressive collapse can be described as a series of smaller failure that ends in partial collapse or whole structure collapse which is not proportional to the original local damage. The early local damage could be loss or damage of a column or load-carrying-wall. Improper design, erroneous construction and unusual loads like internal gas explosion, blast, fire, vehicular collision, aircraft impact, earthquake etc. can be factors for such type of collapse.

1.2 DEFINITION AND MECHANISM

ASCE 7 (2010) defines progressive collapse as "the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it" [1].

The National Institute of Standards and Technology (NIST) defines progressive collapse similar to that of ASCE 7(2010): "Progressive collapse is the spread of local damage from a single initiating event, from structural element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it. This type of collapse is also known as disproportionate collapse" [2].

According to the U.S. GSA 2016, progressive collapse is "an extent of damage or collapse that is disproportionate to the magnitude of the initiating event". As the definition emphasises on the final result and magnitude of failure rather than the way it occurs, it is also known as a disproportionate collapse in industrial field [3].

Progressive collapse is a dynamic event wherein a localised damage is propagated to the adjacent structural elements that leads to partial failure or failure of the entire structure disproportionate to the initial damage. The early local damage could be loss or damage of a column or load-carrying wall. The nature of the event is dynamic which is evident from the fact that vibration is initiated when a load-bearing structural element is failed. This leads to redistribution of internal forces so as to absorb the energy created and stabilize the structure. Consequently, the structure is partially failed or complete collapse takes place [4].

1.3 BACK GROUND

Structural engineers have been drawn to a number of worldwide catastrophic progressive collapses. Few of them are Ronan Point (London, 1968) and Capitan Arenas (Barcelona, 1972), the U.S. Marine Barracks (Beirut, 1983), the Argentine Israelite Mutual Association (Buenos Aires, 1994), the A.P. Murrah Federal Building (Oklahoma, 1995), the Sampoong Department Store (Seoul, 1995), the buildings of the World Trade Center (New York, 2001), and the Achimota Melcom Shopping Centre (Acra, 2012) [5].

1.3.1 Ronan Point Building Apartment collapse

Ronan Point was a 22-storey building in London where an explosion caused by gas leakage destroyed the load-carrying wall. This led to the failure of corner of the whole structure [6].

Figure 1.1 Ronan Point Apartment (From http://www.geograph.org.uk/reuse). Image copyright © Derek Voller.

1.3.2 Alfred P. Murrah Building Collapse

On 19th April 1995, the Alfred P. Murrah Building was partially collapsed due to bombing. In this incident, 167 persons died and 782 persons injured. And the loss of property was worth $652 million [7].

Figure 1.2 Alfred P. Murrah Building before and after the collapse.

1.3.3 World Trade Centre Tower Collapse

As per the official probe, the catastrophic failure of Twin Towers was caused by the plane collision with the tower resulted into progressive collapse which caused great loss [8].

Figure 1.3 Twins Tower, New York (2001)- A case of Progressive Collapse (Source:http://www.dailymail.co.uk/news/article-2040657/Explosions-caused-jet-fuel-water-sprinklers-brought-TwinTowers-9-11-scientists-say.html).

1.4 SIGNIFICANCE

Progressive collapse is not a common event though its aftermath can be disastrous. There can be a great loss of life and property. India and its neighbouring countries has been witnessed many notorious activities in in the past. There are no codes or guidelines in many countries for the collapse since the event is rare. Keeping in mind the rise in terrorism at global level and disturbances associated with it, research in this field becomes essential.

1.5 OBJECTIVES

The objectives of the work are mentioned below:

1. To analyse the 3-D model by using non-linear dynamic approach of progressive collapse analysis for three different positions of column elimination i.e. corner, penultimate and middle column removal cases in R.C. building.
2. To identify the variations in response with respect to the change in input parameters.
3. To generate mathematical models of vertical deflection of the upper node for three different cases.
4. To optimize the generated mathematical models.

1.6 ORGANISATION OF DISSERTATION

The present dissertation has been divided into five chapters which are organised as given below:

Chapter 1: It contains general concept, mechanism, past incidents related to progressive collapse and significance as well. It also includes layout of the dissertation as well as its objectives.

Chapter 2: This chapter presents bibliometric analysis and review of the literature from the beginning to the most recent advancements and additional studies of progressive collapse reported by various authors and research scholars. Based on research gap, objectives are formulated.

Chapter 3: It addresses research methodology, assumptions, design parameters and generation of mathematical model.

Chapter 4: This chapter discusses mathematical model for response, tests the adequacy of model, sensitivity analysis of influential parameters and discusses about simulation and optimization based results.

Chapter 5: It deals with the summary of the conclusion obtained from the work.

1.7 SUMMARY

This chapter contains general concept, mechanism and past incidents related to progressive collapse as well as its significance. Objectives and layout of the dissertation has been covered here.

CHAPTER 2

LITERATURE REVIEW AND BIBLIOMETRIC ANALYSIS

2.1 INTRODUCTION

This chapter begins with a review of the basics and progresses through developments and additional studies in progressive collapse of building structure that have been published by various researchers.The literature reviews cover broadly theoretical and simulation based work as well as experimental work. A bibliometric analysis have been performed in the area of progressive collapse for a span of twenty years.

2.2 LITERATURE REVIEW

Marjanishvili, S.M. [4] applied four different methods for analysis of progressive collapse analysis and compare with each other in terms of advantages and disadvantages. Linear dynamic, linear static and nonlinear dynamic are considered most effective approaches. In this approach non-linear dynamic analysis is the most exhaustive one and static linear elastic is the simplest one.

Xiao et al. [9] employed new method "virtual thermal pushdown analysis" in progressive collapse of RC structure. In this the displacement-temperature curve produced, shows the real nonlinear connection between the structural performance (vertical displacement) and quantity of reinforcement. The quantity of reinforcement at the specified performance target is thus directly determined using this curve.

Lim et al. [10] developed an analytical model to estimate the resistance of affected structure under progressive collapse and provided a quick check for suitability of progressive collapse resistance in order to avoid remaining structure damage by propagation of local failure.

Tsai et al. [11] reported with the rise-time effect in consideration, an approximate analytical formulation for the maximum dynamic response is obtained based on the work-energy principle. The correctness and validity of the suggested formulation are evaluated using displacement and the force-based dynamic increase factors (DIFs) of a single degree-of-freedom model and a clamped steel beam. The DIFs decrease as the rise time increases and with higher ductility demand, the rise-time effect also drops according to the results of the analysis.

Mohajeri et al. [12] presented a simpler theoretical model for assessing RC frames after the elimination of the middle column. The suggested model predicts the general behaviour of an RC frame in four stages when the middle column is removed, and the practical and theoretical results accord well. The suggested model is straightforward, practical, and easy to grasp, which reduces computation time and simplifies the prediction of RC frame ultimate capabilities.

Elsanadedy et al. [13] reported the progressive collapse-resistant capacity of steel moment resisting frames using alternate path methodologies prescribed in GSA and DoD guidelines. For comparison, linear static and nonlinear dynamic analysis methodologies were used. The structural reactions were bigger in nonlinear dynamic analysis than the linear elastic, and the findings changed considerably based on factors like position of column removal, number of building stories or applied load, as compared to the linear analysis results.

Gombeda et al. [14] used external blast threats in a threat-dependent progressive collapse assessment on building frames for mapping structural damage. The computed behaviour of discrete structural components (especially the columns) to a blast-induced pressure time history is used to map structural damage. For, direct shear, flexure and breach failure modes, this model can be utilised to assess the final damage status of crucial column sites.

Feng et al. [15] performed sensitivity analysis on RC structure under column removal case. They used Tornado diagram for strength of tensile catenary action and compressive arch action with respect to compressive strength of concrete, diameter of bar and yield strength of reinforcement, these parameters depicted significant effect on the capacity of progressive collapse behaviour.

Azim et al. [16] predicted capacity of RC building behaviour in terms of catenary action using gene expression programing (GEP). In this study the input influential parameters were selected as stiffness of relative rotational restraints and relative axial restraints, ratio of double beam length to depth, longitudinal rebar's' yield strength. For pre-design objectives, GEP's recommended formulation is found to be simple, sturdy, and straightforward to use.

Li et al. [17] investigated robustness analysis of RC structure based on building height influence. They found that high rise building is more robust with respect to lower stories building, with initial column removal of corner column at lowest floor.

Li et al. [18] proposed probability index of collapse to estimate the resistance of progressive collapse in RC structure. Instead of assessing any specific beginning local failures, such an index can measure all usual initial local failures. The fragility curve of collapse is further defined by this index, which fluctuates as nominal gravity increases.

Feng et al. [19] proposed a new method probability density evolution method (PDEM) to investigate structural reliability and structure response in terms of progressive collapse behaviour. Under pushdown method of column removal case, structure's robustness and reliability indices are calculated and the effects of the first damage scenarios' position on the robustness are examined.

Sasani [20] performed FEM and AEM based analysis employing removal case of simultaneous two outer columns to evaluate local as well as global deformations on 6 story RC frame structure. As per the response, the displacement is around 1.8 times that achieved when the infills are modelled using shell elements and element cracking is taken into account.

Adam et al. [21] performed the experimental analysis of a full-scale RC cast-in-situ building structure exposed to a sudden column failure of corner location is described in their work. After the corner-column was abruptly removed, the structure was able to discover effective alternate load routes, and the observed dynamic amplification did not cause substantial structural damage. The peak dynamic values were significantly greater than the stabilised residual values following the time-history test, according to the results. For the case under investigation, the flexural and Vierendeel beam actions were the most common ALPs in the test whereas slab membrane action was not an important ALP.

To investigate the differences between the UDL's resisting mechanisms, **Pham et al. [22]** performed progressive collapse experiments under a corner column removal scenario on a two-fifth-scale RC frame with slab by quasi-static loading.

For evaluation of the resilience of beam-slab substructures to progressive collapse, **Qian and Li [23]** conducted practical research on three quarter-scale samples for RC frames with slabs. To forecast the dynamic displacement of specimens in dynamic phase, SDOF models are used. It was discovered that SDOF could accurately forecast peak dynamic displacement while overestimating vibration and underestimating permanent residual deformation.

Jun et al. [24] conducted an experiment on two specimens, made of seven beams and two square slabs under column removal case of penultimate exterior and perimeter middle. Progressive collapse resistance as well as the mechanism of load transfer of the frame were shown using proper instrumentation.

Sadek et al. [25] examined the behaviour of reinforced concrete and steel beam-column assemblies under monotonic vertical movement of a middle column, representing a column elimination case experimentally as well as computationally. The assemblies are parts of 10-story structural framing systems intended for Seismic Design Categories C and D, respectively, as intermediate moment frames (IMFs) and special moment frames (SMFs).

Joshi and Patel [26] used precast dry connection with one-third scale of the assembly and compared its performance with that of monolithic dry connection in their experiment.

Lim et al. [27] performed experiment to investigate the role of slabs in the resistance and behaviour of frame-slab systems exposed to point loads for corner column loss has been studied and found that on top of the frame's maximum flexural capacity, the slab flexural capacity added roughly 55 percent more capacity and tensile membrane action could not be activated which is indicated by no compressive ring formation.

Naghavi and Tavakoli [28] investigated the performance of a special steel moment-resisting frame structure during progressive collapse using probabilistic analytic approach. To estimate the collapse probability, Monte-Carlo Simulation coupled with RSM and ANN was used and thus huge computational time was saved. It was observed that ANN was better than RSM method while estimating structural responses. Sensitivity analysis was also performed and found that its result can be used to retrofit the structures influenced by progressive collapse.

2.3 BIBLIOMETRIC ANALYSIS

2.3.1 Data Source

The research data is taken from scopus database by searching keywords like “progressive collapse analysis”, “RC building”, “Non linear dynamic analysis”. Initially documents sources were journals , book chapters , books, conference review , review papers and later books chapter and books are excluded and time span is limited to 2002 to 2021. Table 2.1 depicts basic information of data source and its type.

Table 2.1 Primary Information of Data

S. No	Description	Outcomes
A	**Data Basic Information**	
	Time duration	2002:2021
	Sources	203
	Documents	531
	Average years from publication	5.75
	Mean citations /paper	13.14
	Mean citations /year /paper	1.883
	References	11758
B	**Types of Document**	
	Article	362

Table 2.1 (Continued)		
	Conference Paper	143
	Conference Review	21
	Review	5

2.3.2 Result analysis

After using biblioshiny in R package bibliometrix and vosviewer for network and bibliometric analysis [29, 30] the following key results are discussed in the following sections.

2.3.2.1 Three Fields Plot

Fig. 2.1, using Sankey diagram as shown in, represent the important elements in three fields namely authors, keywords, and journals and how they're linked. The left field shows the source or journal name and middle one represents author's name who contributes the research publications. The right field's elements depict research topics that conducted by different researchers with theme of progressive collapse analysis, robustness, finite element analysis etc. in the field of concrete building structure. The rectangle's size reflects the huge number of research articles linked to each of these parts. Here the red colour rectangle in the left field illustrates maximum no of research article published under the "Engineering structure" journal out of 18 indexed journals with major theme of progressive collapse analysis in structural engineering. In the middle elements authors name is shown that linked with associated journal and the topics. The size of the rectangle indicates number of research articles published by different authors. The right elements show the different keywords used in the article. Here, the keywords progressive collapse, robustness, reinforced concrete etc. is high in number as their rectangle size is bigger and rectangle size of keyword progressive collapse is the largest amongst all. So, this demonstrates that the term progressive collapse or robustness or reinforced concrete is intimately linked to study on the progressive collapse in concrete engineering structure studies.

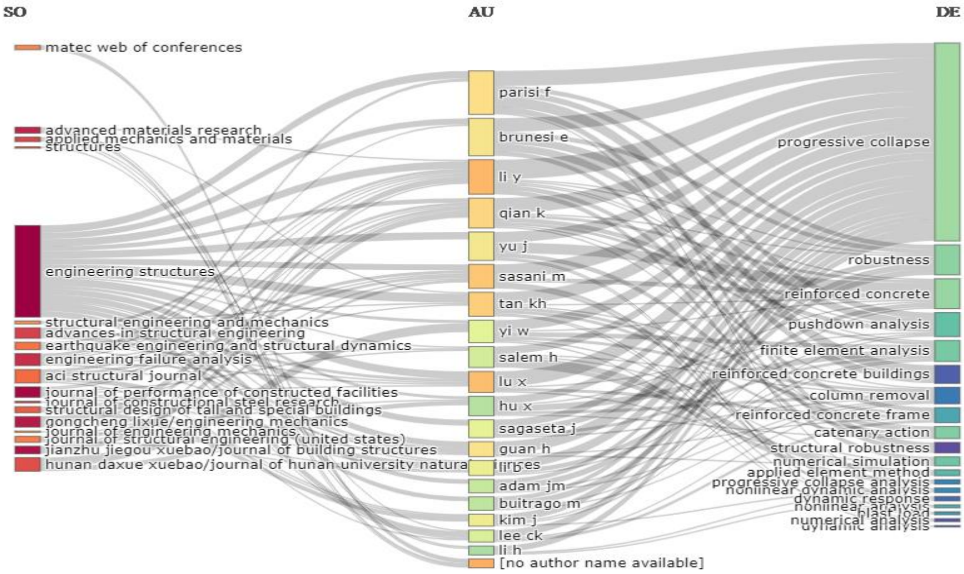

Figure 2.1 Three field plot with source journal and key words

Similarly, Fig.2.2 shows the three field plot with author in the middle, Author's country is kept in the left and author's university is placed right side of the author.

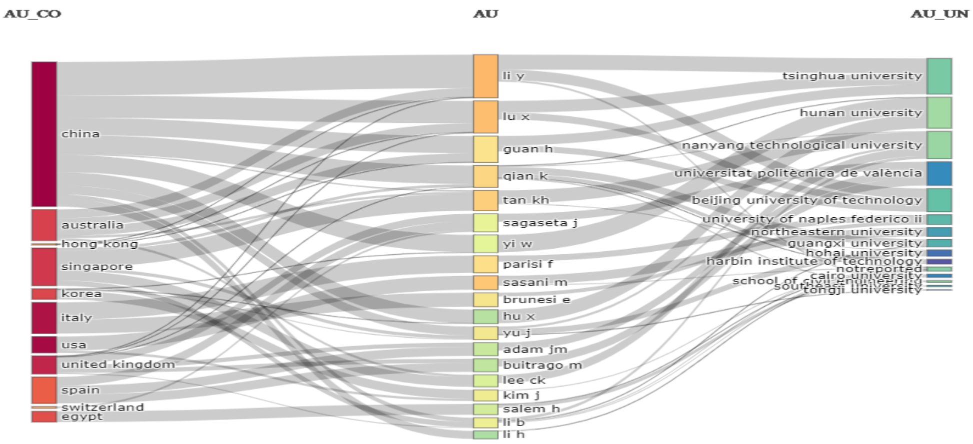

Figure 2.2 Three field plot with author's country and university

2.3.2.2 Most Cited Countries and Relevant Affiliation

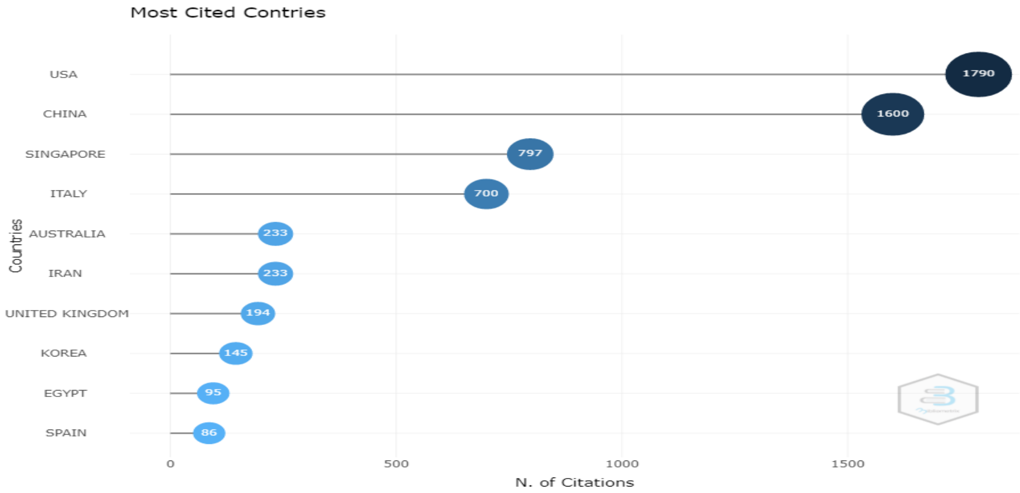

Figure 2.3 Most cited countries

Fig. 2.3 depicts most cited countries in the field of progressive collapse. USA, China and Singapore are among the top three in list. Fig. 2.4 depicts the most relevant affiliations with respect to article published. Hunnan University placed at top in the list with 56 articles and Shanghai Jiao Tong University placed at the bottom.

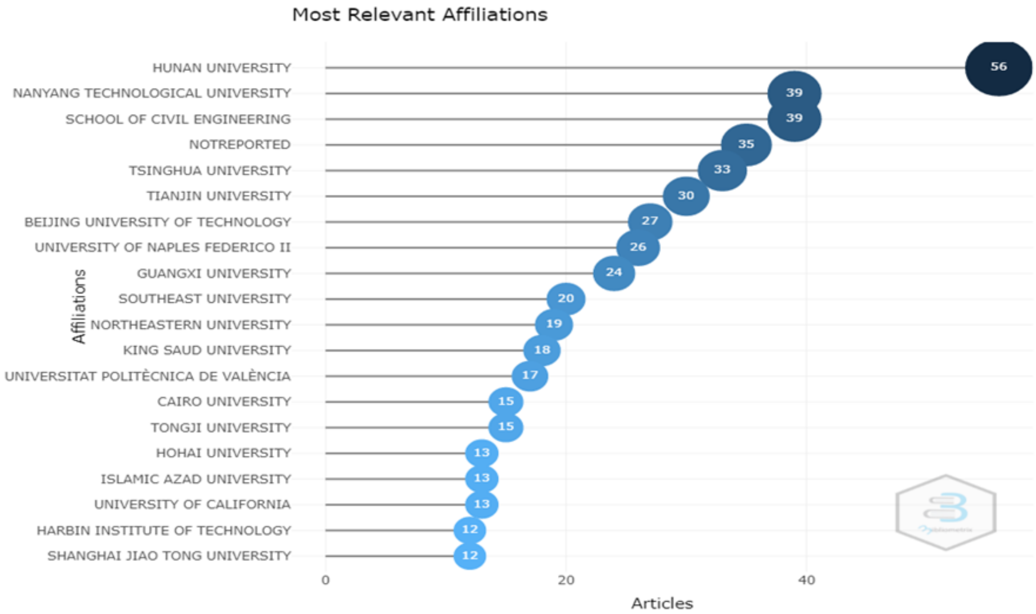

Figure 2.4 Most cited organisations

2.3.3 Bibliographic coupling

The term bibliographic coupling was first introduced by Dr. M.M Kessler in 1961 and it is defined as “a single item of reference shared by two documents is defined as a unit of coupling between them” [31]. The current study focussed on bibliographic coupling of sources with weightage of documents and coupling of documents based on citations. Here 22 sources are clustered into 6 groups with different colour codes and threshold limit of 5 documents as shown in Fig. 2.5. It is clearly shown that engineering structures nodes are the largest amongst all groups. The top three sources are engineering structures, journal of performance of constructed facilities and engineering failure analysis. In Fig. 2.6 coupling of documents are shown with weightage of citations having threshold limit of 10. Here, Yu J. (2013) with 216 citations and total link strength of 112 ranked top in the list. Mohajeri Nav F. (2016) and Yu J. (2020) are with minimum citation of 10 placed bottom in the list.

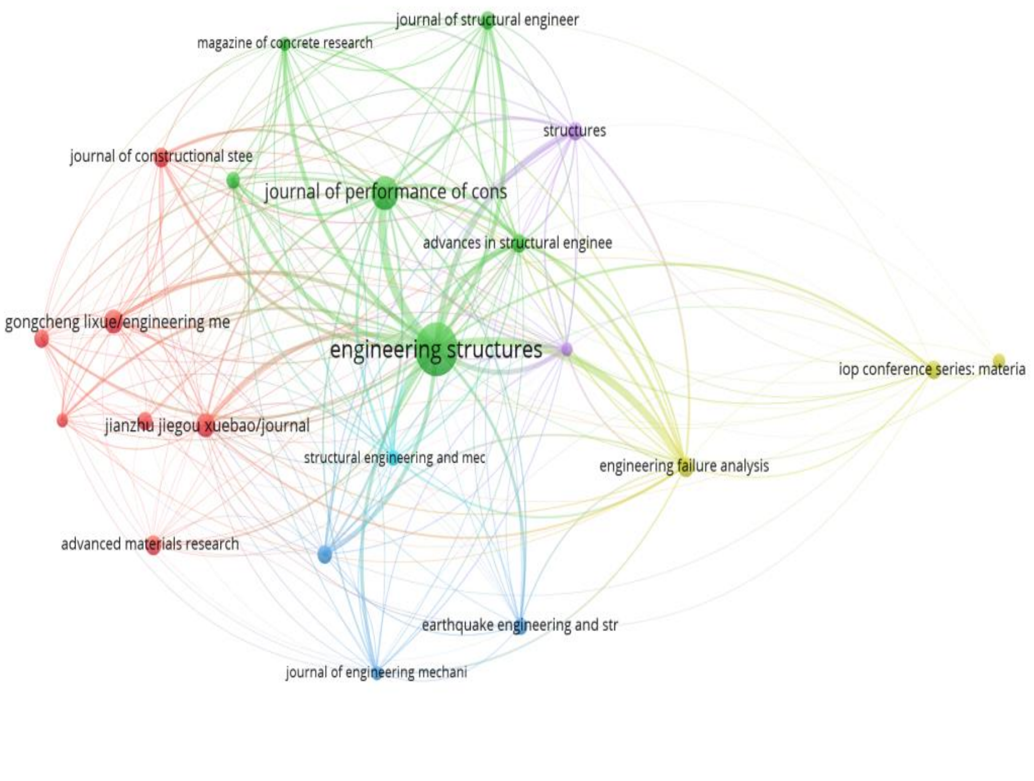

Figure 2.5 Bibliographic coupling of sources

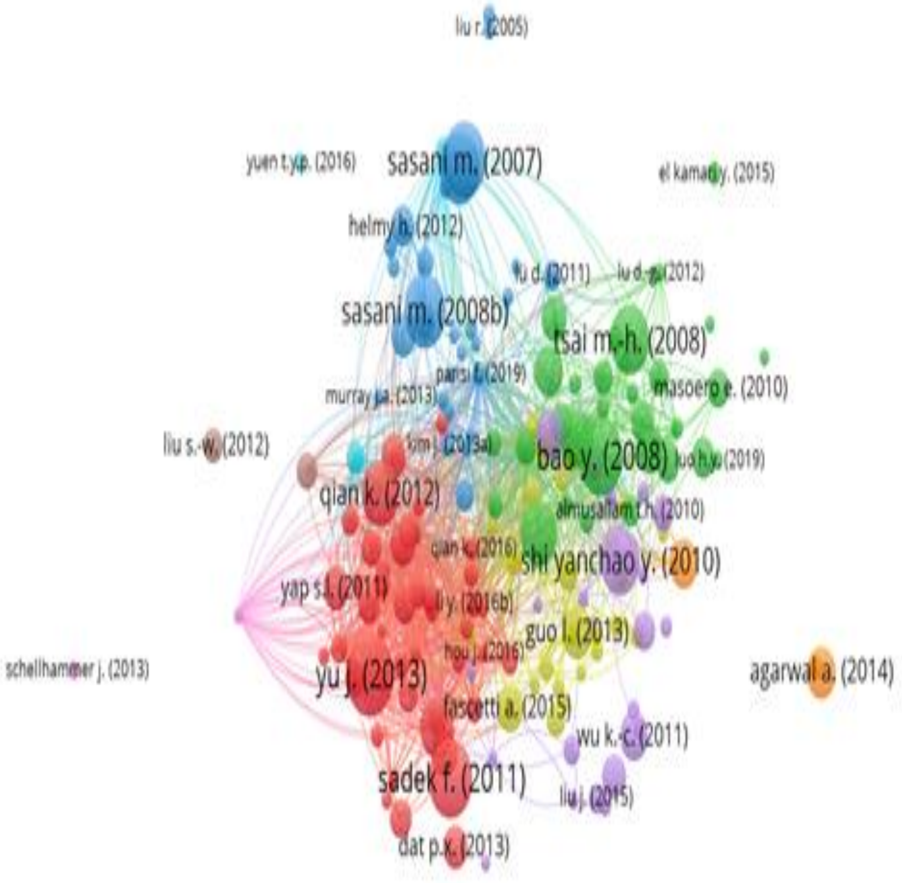

Figure 2.6 Bibliographic coupling of documents

2.3.3.1 Co-citation Analysis

The term "co-citation analysis" refers to a method of determining that authors, journals, keywords, and themes all have a link. It is used to determine the correlation degree between two different articles. When two papers contain one or more of the same references, this is known as a co-citation [32]. If this technique is employed to publications, it reveals a field's intellectual structure as well as the evolution and research variations over the span of time. On the other hand, when applied to writers, co-citation analysis identifies the nature of their social interactions [33] as shown in Fig. 2.7.

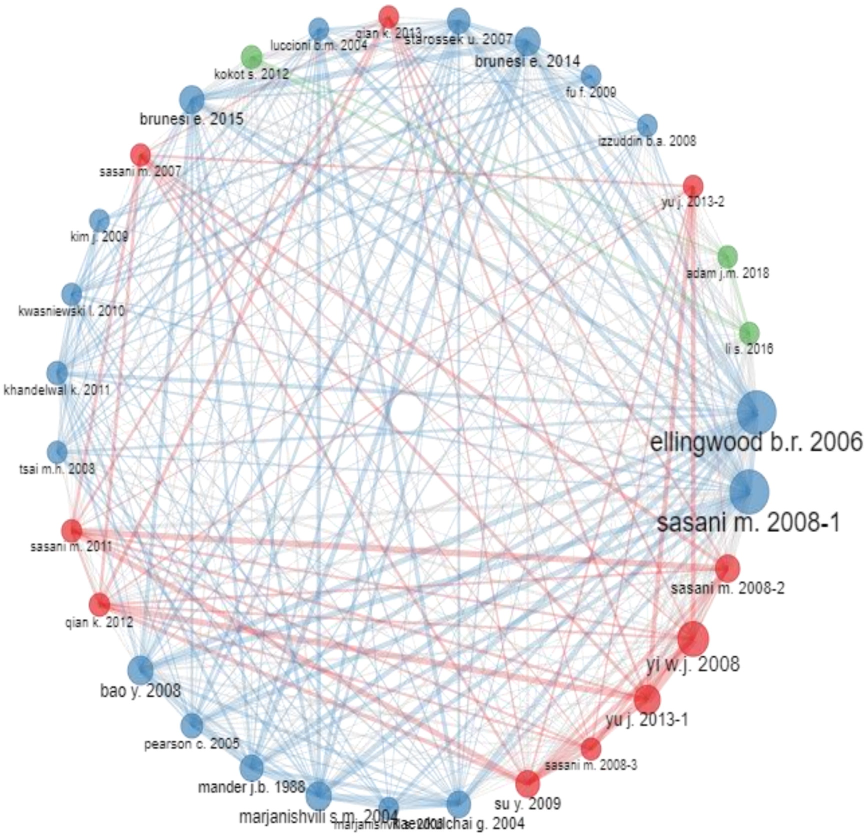

Figure 2.7 Co-citation network.

2.3.3.2 Keywords analysis

The keyword analysis in paper is a critical approach for understanding what's hot in the field and where academics are concentrating their efforts [34]. This inquiry is required since keywords of publication aid in quickly establishing a publication's topic and its focus area.

In Fig.2.8, word cloud depicts the most frequent words are reinforced concrete, progressive collapse, structural dynamics, and FEM in progressive collapse analysis of concrete structure. Fig.2.9 depicts the word dynamics of the title, abstract as well as writers' most frequently used keywords. Majority of these keywords first appeared in the field of research about 2006 and have increased in recent years as seen in the graph. While some of them, like reinforced concrete and progressive collapse after 2007, began to see tremendous growth.

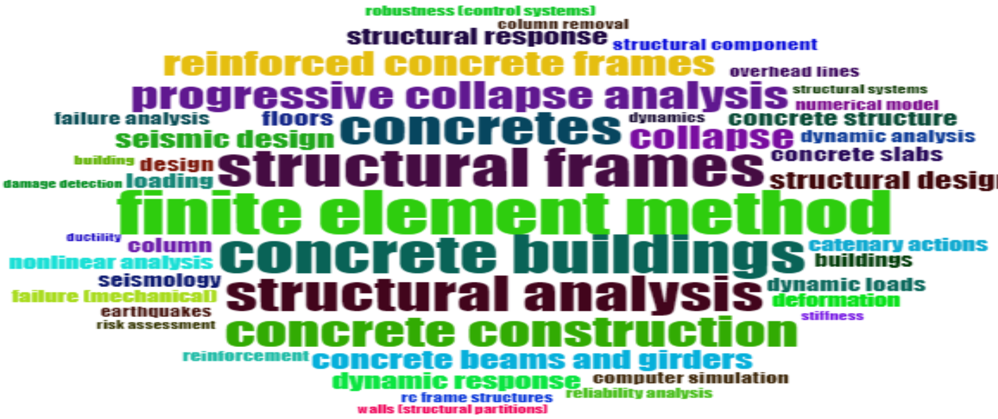

Figure 2.8 Word cloud

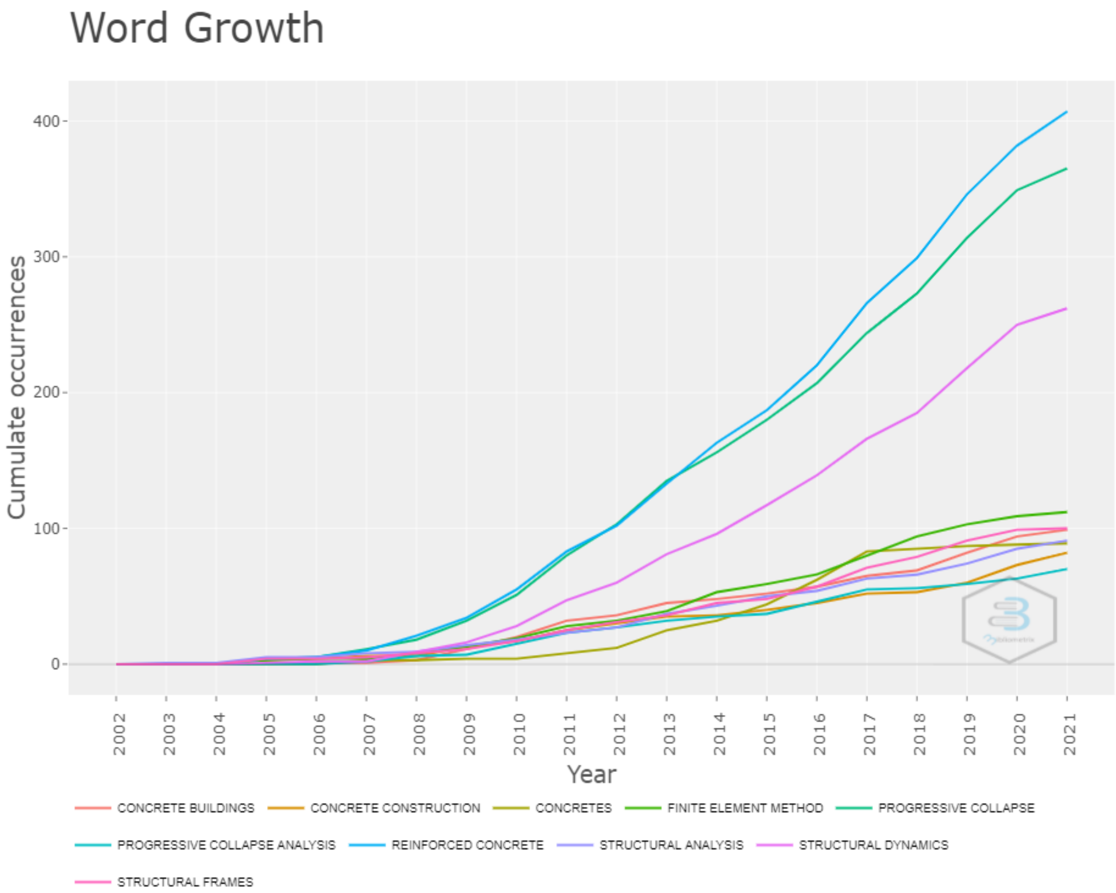

Figure 2.9 Word growth

2.3.3.3 Co-occurrence network

The keywords co-occurrence network (KCN) was explored so as to acquire an enhanced grasping of the trends in the field of progressive collapse analysis of concrete structure. The KCN analysis shows how keywords in literature are linked, looking deeper into the area's knowledge structure [35]. Here keywords are distributed in seven different cluster based on weightage of total link strength with total count method. The size of nodes signifies the number of times the particular type keywords used and the connections between two keywords are depicted by different thickness of lines. The degree of closeness between two keywords is represented by thickness of lines as shown in Fig. 2.10. In Fig. 2.11 overlay visualization is depicted with scores of average publication per year from 2012 to 2018 sessions. The yellow colour shows 2018 published paper with topics of parametric analysis, experimental study, and column removal in the domain of progressive collapse of concrete structure.

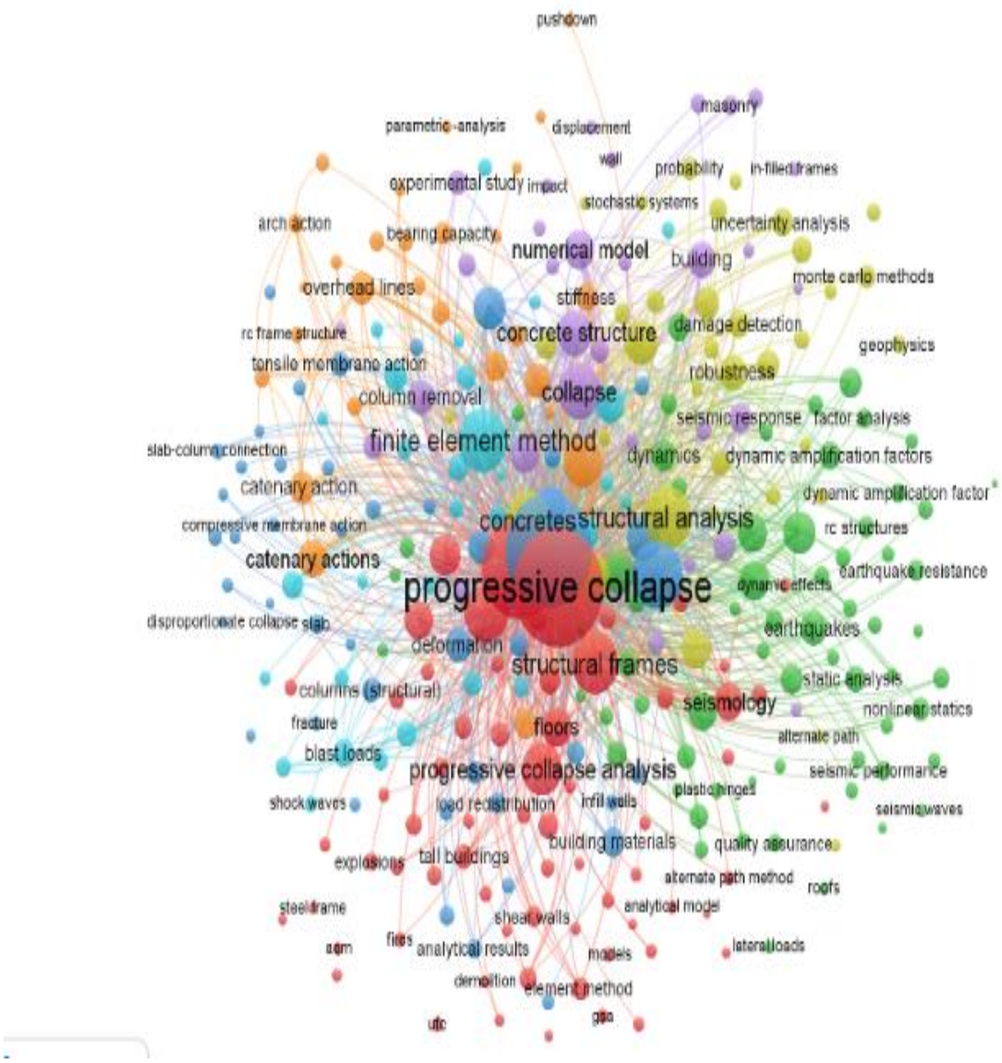

Figure 2.10 Co-occurrence

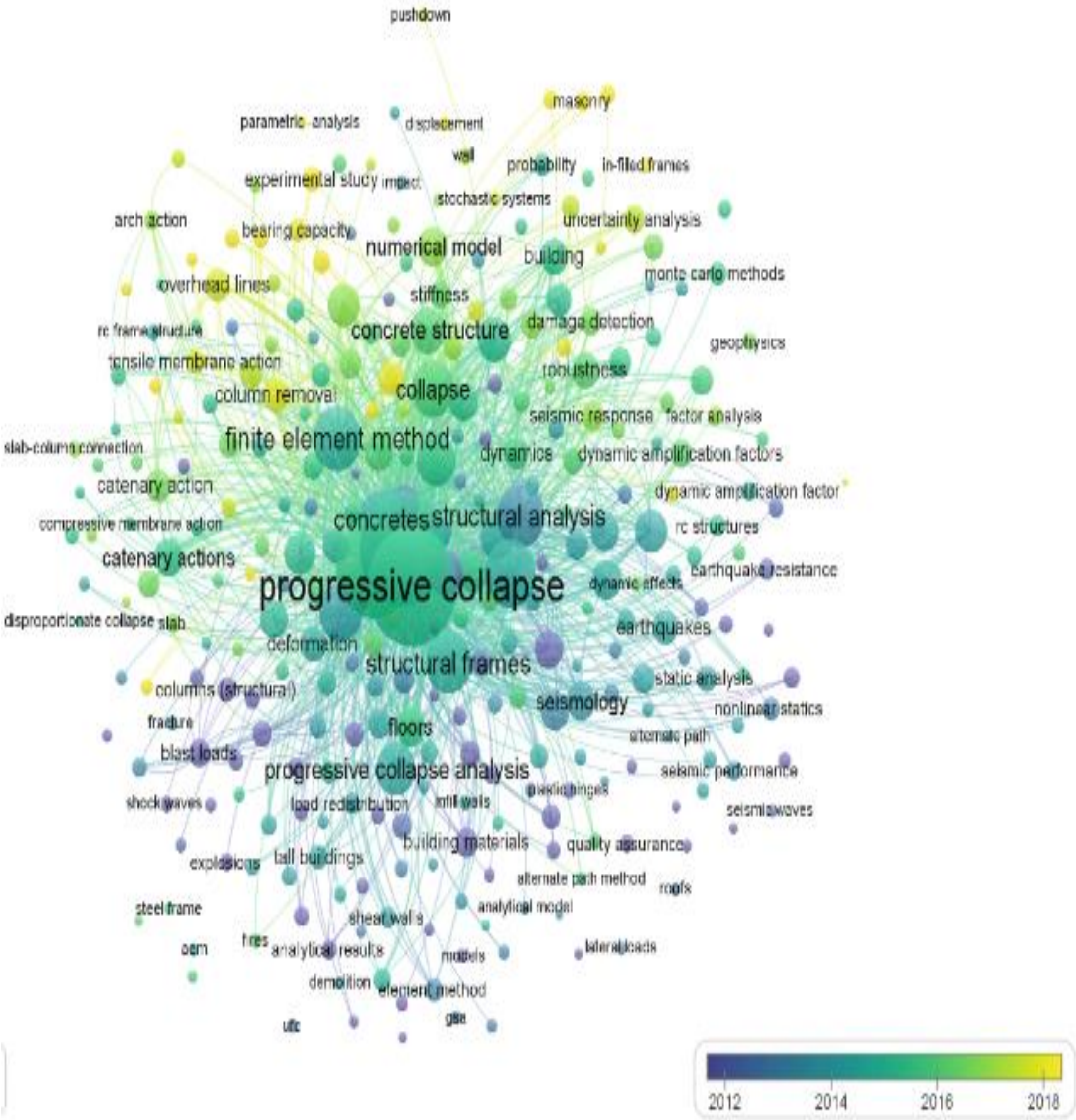

Figure 2.11 Overlay visualization

2.3.3.3 Trend in topics

Fig.2.12 depicts the keywords trend with respect to time. Different size of dots depicts the keyword's frequency against the corresponding keywords. The bigger size illustrates higher frequency and smaller one shows lower frequency. So precast concrete, bearing capacity and accident topics are trending in 2020 which is clearly shown in the figure. The reinforced concrete and progressive collapse are one of the top frequency keywords amongst all.

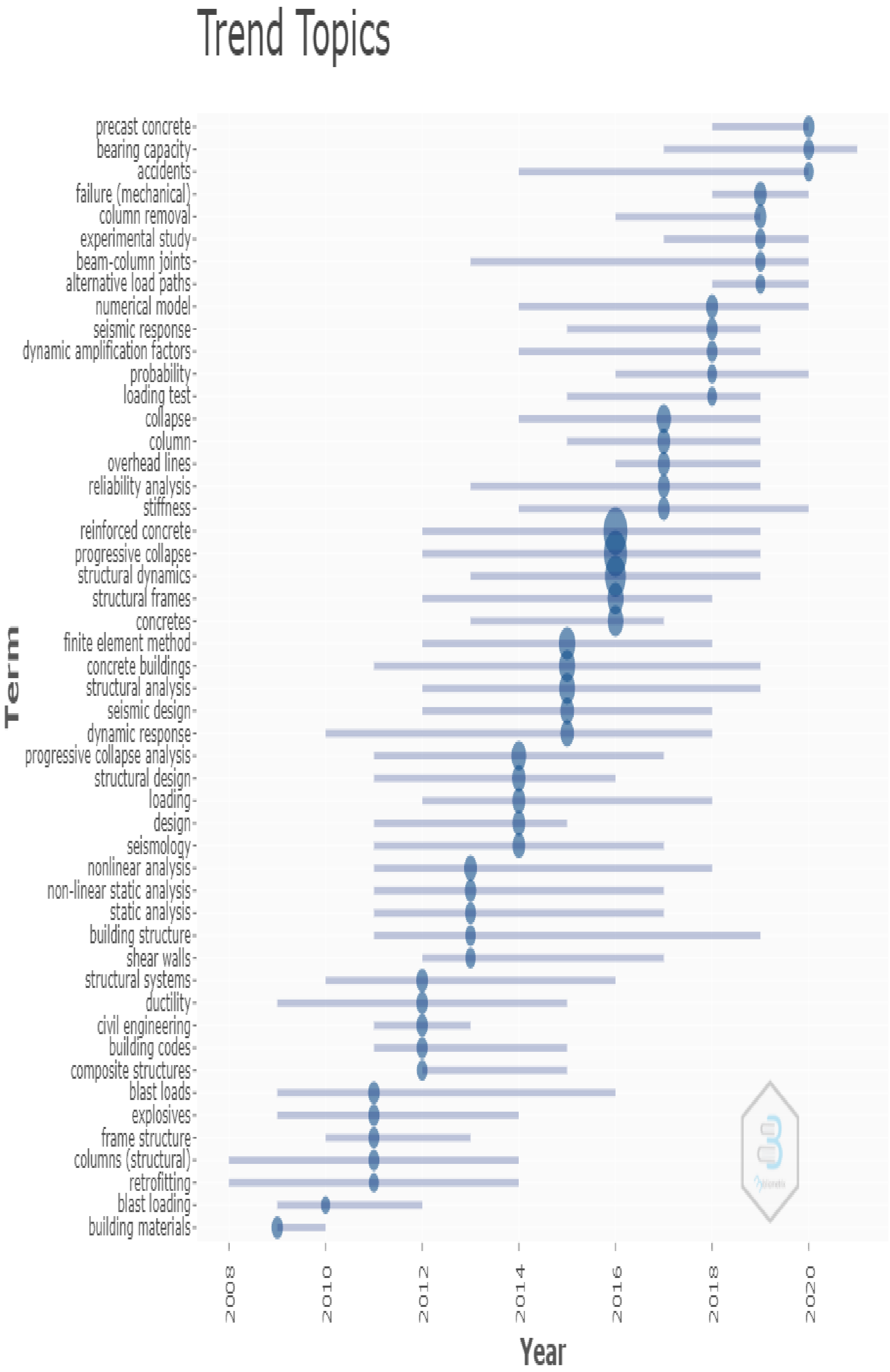

Figure 2.12 Topics in trend

2.4 RESEARCH GAP

Earlier different authors and researchers worked on progressive collapse analysis theoretically as well as experimentally. But parametric and sensitivity analysis have been rarely investigated. Generally, researchers used conventional methods like Monte Carlo simulations, conditional probability etc. but RSM approach have been rarely touched. The following research gaps have been identified based on the literature reviews.

1) Very few researchers reported sensitivity analysis of critical sections in the progressive collapse.
2) There is a lack of mathematical modelling of concerned critical sections undergoing local failure.

2.5 SUMMARY

This chapter illustrates that the field of progressive collapse is at peak and its trend sharply rose after 9/11 incident in USA. As per the word growth analysis, reinforced concrete, progressive collapse and structural dynamics are fastest growing keywords in structural engineering. The sub-research areas of progressive collapse are robustness, reliability, numerical simulation and finite element analysis. The top three sources i.e. engineering structures, journal of performance of constructed facilities and engineering failure analysis have been identified on the basis of bibliographic coupling with weightage of total documents count. USA, China and Singapore are among the most cited countries with progressive collapse as their main research topic.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter discusses about the research approach and techniques related to the progressive collapse analysis of RC structure. Here, nonlinear dynamic approach is employed in progressive collapse analysis in SAP2000 and response surface methodology has been used as a tool for the generation of mathematical model, sensitivity analysis, design of experiment as well as optimisation of the generated model.

3.2 FLOWCHART

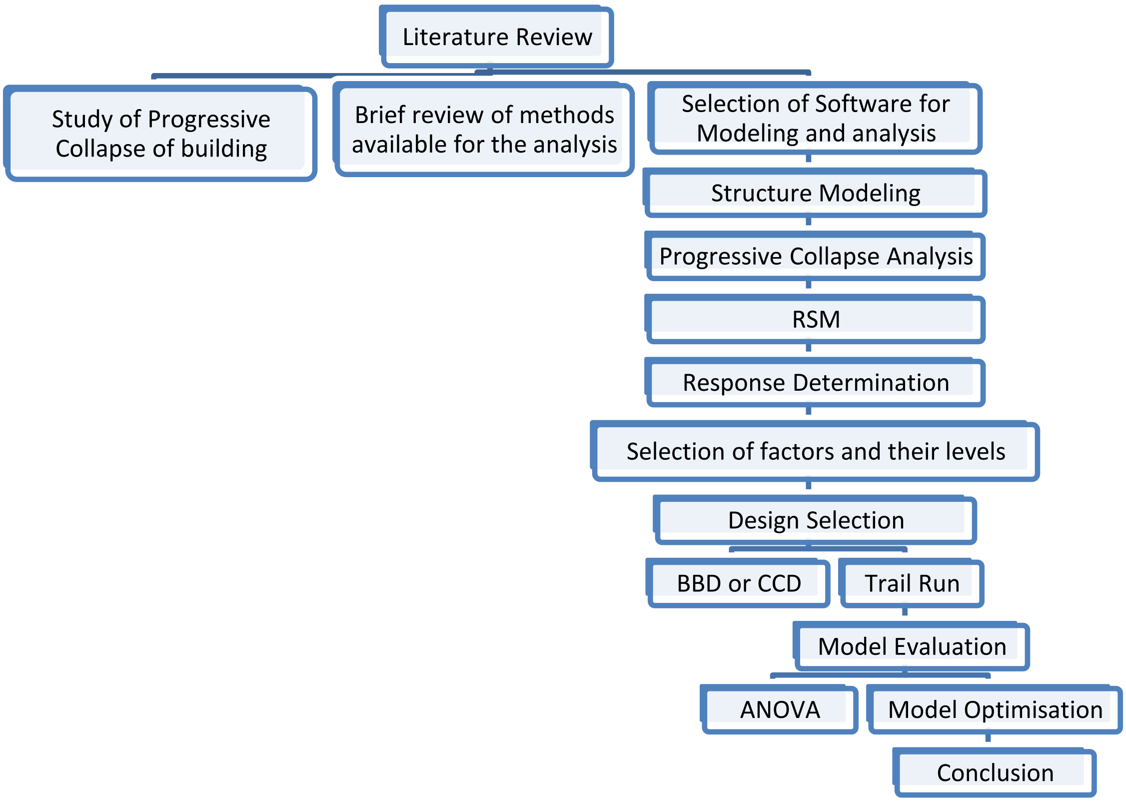

Figure 3.1 Work Methodology including RSM Flowchart

3.3 NONLINEAR DYNAMIC ANALYSIS

Nonlinear method of dynamic analysis to execute progressive collapse is the most comprehensive method of analysis. In this method, a vertical load-bearing element is eliminated and the structural material is permitted to enter nonlinear range. Through material yielding, cracking, and fracture, greater deformations and energy dissipation are possible. Nonlinear dynamic analysis is carried out in the same way as linear dynamic analysis, except that structural components are now permitted to reach their inelastic region. This study was carried out using the initial conditions technique [36]. It involves following steps:

1. A finite-element computer model (Model A) is created by defining material, section, load pattern, load case and applying it on the model. It includes the complete model, as well as the column that will be removed.
2. Analysis is done to obtain the internal forces of the column, to be removed.
3. Another finite-element computer model (Model B) is created, in which column is removed. The column end forces is applied, obtained during the analysis of Model A, to simulate the presence of the removed column.
4. Simulation of the column removal is done by running a time-history analysis. During the analysis these equivalent column loads are decreased to zero over a short stretch of time. This is done by applying a ramp time function in which loads opposite to those of the equivalent column loads are scaled from zero to the full value. The duration of this event should match the time in which the column is removed.
5. Dynamic load combinations are applied as per GSA 2016 guidelines.
6. Nonlinear dynamic analysis is executed with initial conditions. It is accessible as a standard analysis type in the software.
7. The above process is complex as it requires several computer analysis re-runs until a stable and potential solution is established.

3.4 RESPONSE SURFACE METHODOLOGY

To improve the efficacy of any given experiment, a meticulously designed experiment of the design is required which can lead to reduction in iteration as well as to correctness and preciseness of the result. Response surface methodology (RSM) is a commonly adopted mathematical and statistical tool for modeling and analysing a process where the output is affected by a number of factors. In RSM, the Central Composite Design (CCD) or Box-Behnken Design (BBD) is still the most commonly used fractional factorial design. In this design, center points are augmented with a cluster of axial points known as 'star points' which allows estimation of the curvature.

These approaches are employed to obtain high order polynomial equations. For fitting quadratic equation, applies three central with twelve middle edge nodes of cubical design region. BBD is more efficient as compared to other designs like CCD [37]. The key points of BBD are follows as

1) Each independent factors are leveled as low, mid and high values, i.e. generally in coded form as -1, 0, 1.
2) A quadratic model is expected to fit, i.e. it contains an interaction factor, squared and linear terms and one intercepts.
3) The ratio of number of trials with respect to coefficients terms for given model should be in acceptable range of 1.5 to 2.6.

3.5 ASSUMPTION

1) A symmetric building model has been taken to avoid potential analysis complications introduced by asymmetry.
2) Equivalent viscous damping of 5% is assumed throughout the dynamic analysis.
3) Threat independent case is considered for the analysis.
4) All the input factors are assumed to follow normal distribution.
5) Mathematical models are generated based on 95% confidence interval.
6) Soil-structure is not taken into consideration.

3.6 MATERIAL AND MODEL

Material and section properties are mentioned in the Table 3.1 below.

Table 3.1 Material properties and section

Grade of steel	Fe 500
Grade of concrete	M25
Bay length along longitudinal direction	5.5 m
Bay Length along lateral direction	5.5 m
Column section	400×400 mm^2
Beam section	250×400 mm^2
No. of stories	7

3.7 RC Model

Seven-storied reinforced concrete building is taken for the analysis with four bays in longitudinal as well as in transverse direction. Spacing of 5.5 m is provided between columns in both directions. Every story has floor to floor height of 3.5 m. Top view of the model is also shown with grids in Fig. 3.1(a). A three dimensional view of the model is shown in Fig. 3.1(b) with corner column elimination case. Column cross-section is taken 400 mm x 400 mm whereas the cross-section of beam is taken 250 mm x 400 mm. Slab thickness is 150 mm. Beam length, grade of concrete and beam depth are the three factors considered to analyse the influence on the response which is deflection in this case.

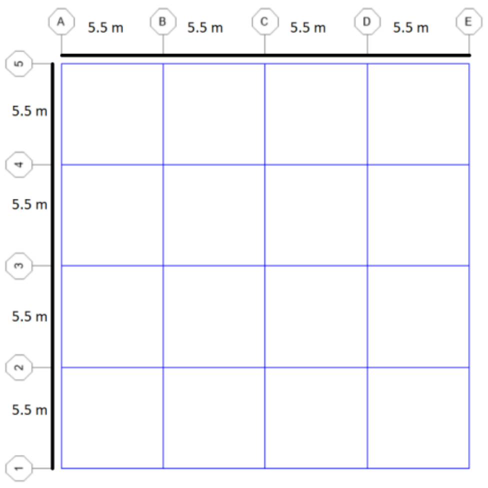

Figure.3.1(a) Plan

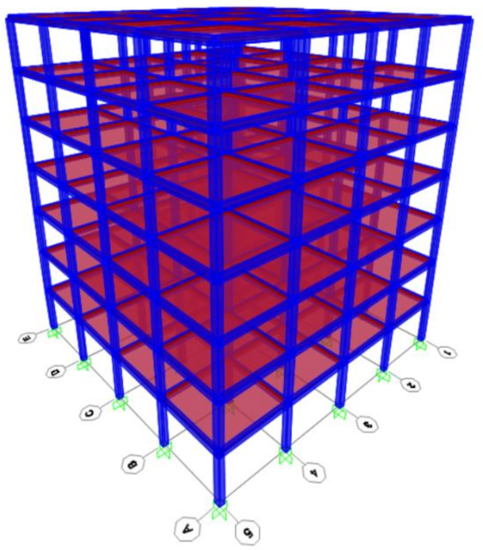

Figure.3.1 (b) Isometric view of the model

3.8 LOADING

U.S. GSA 2016 guidelines [3] gives the gravity load to be imposed on the structure as mentioned below.

$$G_{ND} = 1.2\,D + (0.5\,L \text{ or } 0.2\,S) \qquad (3.1)$$

Where, G_{ND} = Gravity loads for Nonlinear Dynamic Analysis

D = Dead load (lb/ft 2 or kN/m 2)

L = Live load (lb./ft2 or kN/m2)

S = Snow load (lb./ft. 2 or kN/m 2)

Here, BBD method is employed in this study to evaluate the influence of various factors on the response. It includes estimating coefficients, predicting responses, and ensuring that the generated model is acceptable.

Eqn. (3.2) is used to express the output $Y= F\,(x_1, x_{2,}\, x_3 ....x_n)$ (3.2)

Where, Y is the output, F is the response function x_1, $x_{2,......,}$ x_n are the independent variables, and E is the error involved in trials. The second order polynomial is expressed by Eqn. (3.3) [38] as follows

$$Y= a_0 + \sum_{i=1}^{n} a_i\, x_i + \sum_{i=1}^{n} a_{ii}\ \ x_i{}^2 + \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} a_{ij} x_i\, x_j \qquad (3.3)$$

where, a_0 depicts intercepts, a_i, a_{ii}, a_{ij} are coefficient of linear, quadratic and interaction terms respectively. x_i and x_j are process input factors and n is no. of factors.

Table 3.2 Design independent factors and their levels

Factor	Name	Coded Low	Coded High	Mean
A	Grade of concrete (MPa)	-1 (20)	+1(30)	25
B	Beam length (mm)	-1 (5000)	+1(6000)	5500
C	Beam depth(mm)	-1 (320)	+1(420)	400

The current study considered three independent input variables namely grade of concrete, length and depth of beam with three levels as mentioned in table 3.2.

Table 3.3 Experiment Design Matrix

Trial	Factor 1	Factor 2	Factor 3
Run	A:GRADE OF CONCRETE (MPa)	B:BEAM LENGTH(mm)	C:BEAM DEPTH(mm)
1	25	5000	420
2	30	5500	420
3	20	6000	400
4	30	5500	380
5	25	5500	400
6	20	5500	420
7	25	6000	420
8	25	5000	380
9	30	6000	400
10	25	5500	400
11	20	5000	400
12	25	6000	380
13	30	5000	400
14	25	5500	400
15	20	5500	380

3.9 Summary of the chapter

In this chapter basic design approach of nonlinear dynamic analysis of progressive collapse and its limitations have been discussed. Response surface methodology and its classification and their limitations have been explained. The factors of design and their levels and design matrix of BBD have been addressed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

As per the research methodology adopted in the current study, three different positions of column removal case under nonlinear dynamic analysis of progressive collapse analysis coupled with BBD method of RSM have been employed. The response of the vertical deflection is second order polynomial and its adequacy has been addressed as follows.

4.2 CORNER COLUMN ELIMINATION CASE

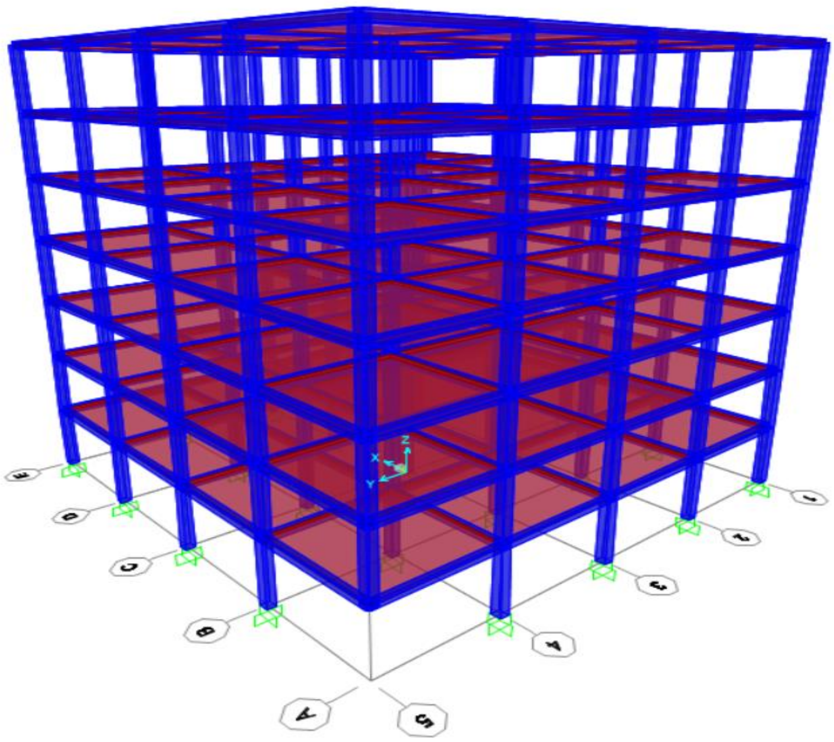

Figure 4.1 Corner Column (5A) Removal Case

Table 4.1 Analysis of variance – Corner Column

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	18596.06	9	2066.23	2775.42	< 0.0001	significant
A-GRADE OF CONCRETE (MPa)	992.13	1	992.13	1332.66	< 0.0001	
B-BEAM LENGTH (mm)	16790.28	1	16790.28	22553.18	< 0.0001	
C-BEAM DEPTH (mm)	550.62	1	550.62	739.61	< 0.0001	
AB	24.50	1	24.50	32.91	0.0023	
AC	2.21	1	2.21	2.96	0.1459	
BC	40.96	1	40.96	55.02	0.0007	
A^2	19.72	1	19.72	26.49	0.0036	
B^2	159.20	1	159.20	213.84	< 0.0001	
C^2	3.96	1	3.96	5.33	0.0691	
Residual	3.72	5	0.7445			
Lack of Fit	3.72	3	1.24			
Pure Error	0.0000	2	0.0000			
Cor Total	18599.78	14				
R^2	=0.9968					

Table 4.1 shows analysis of variance (ANOVA) test result for quadratic model of the vertical deflection of the upper node caused by column removal as mentioned in equation (4.1). The p-value below 0.05 signifies the model accuracy as well as individual model terms at 95 % confidence interval. The Model F-value of 2775.42 implies the model is significant. Having large F-value, there is only 0.01 % chance that it could happen as a result of noise. In this case A, B, C, AB, BC, A^2, B^2 are significant model terms.

$$V.D. = -1{,}186.76 - 4.37475 * A + 0.53329 * B - 0.912938 * C - 0.00099 * A*B + 0.007425 * A*C - 0.00032 * B*C + 0.09245 * A^2 - 2.6265e\text{-}05 * B^2 + 0.00259063 * C^2 \quad (4.1)$$

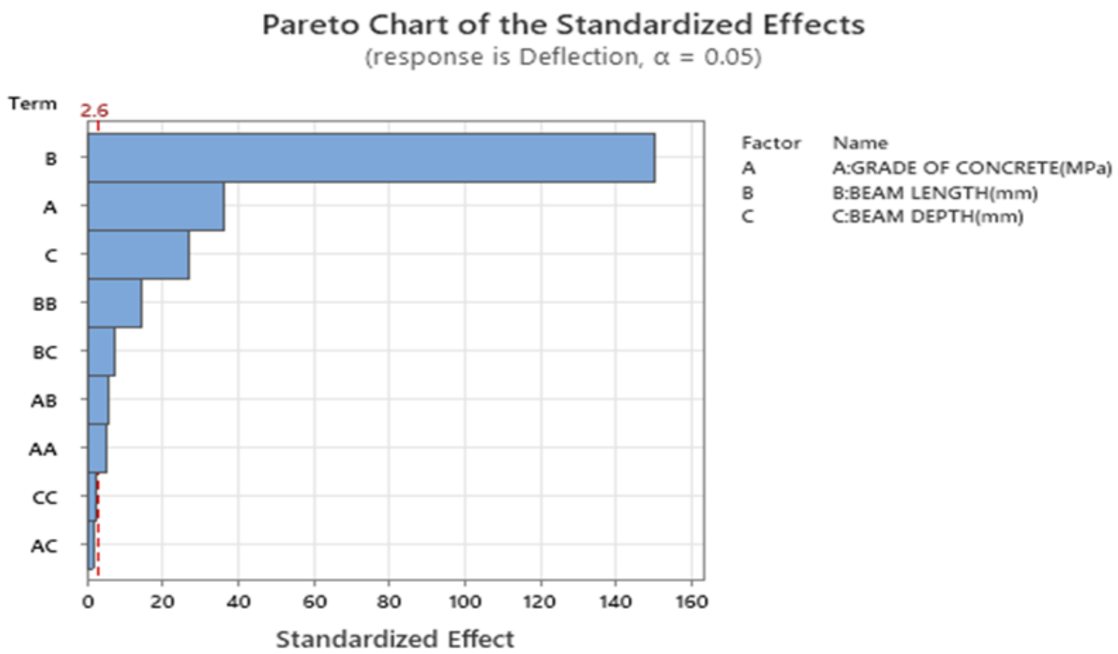

Figure 4.2 Pareto Chart

In Fig. 4.2 Pareto chart described the significance and magnitude of the effects of different terms. From this chart it is clearly shown that factors A, B, C, A^2 and B^2 crossed the reference line of 2.6 value that depict terms are statically significant at significance level of $\alpha = 0.05$ for the current model. The major effect caused by term B (beam length) followed by term A (grade of concrete), term C (beam depth) and term

B^2, term BC, term AB and term A^2. The terms C^2 and AC are close to the reference line but these terms are not significant.

4.2.1 Diagnostic Plots

The diagnostic plots like predicted vs. actual as well as normal probability vs. studentized residual plot give model adequacy. In Fig. 4.3 (a) residuals depicts normal distribution pattern with little scattering along a straight line, as the data is normally distributed. Fig. 4.3 (b) shows a strong correlation between the actual and predicted values of vertical deflection.

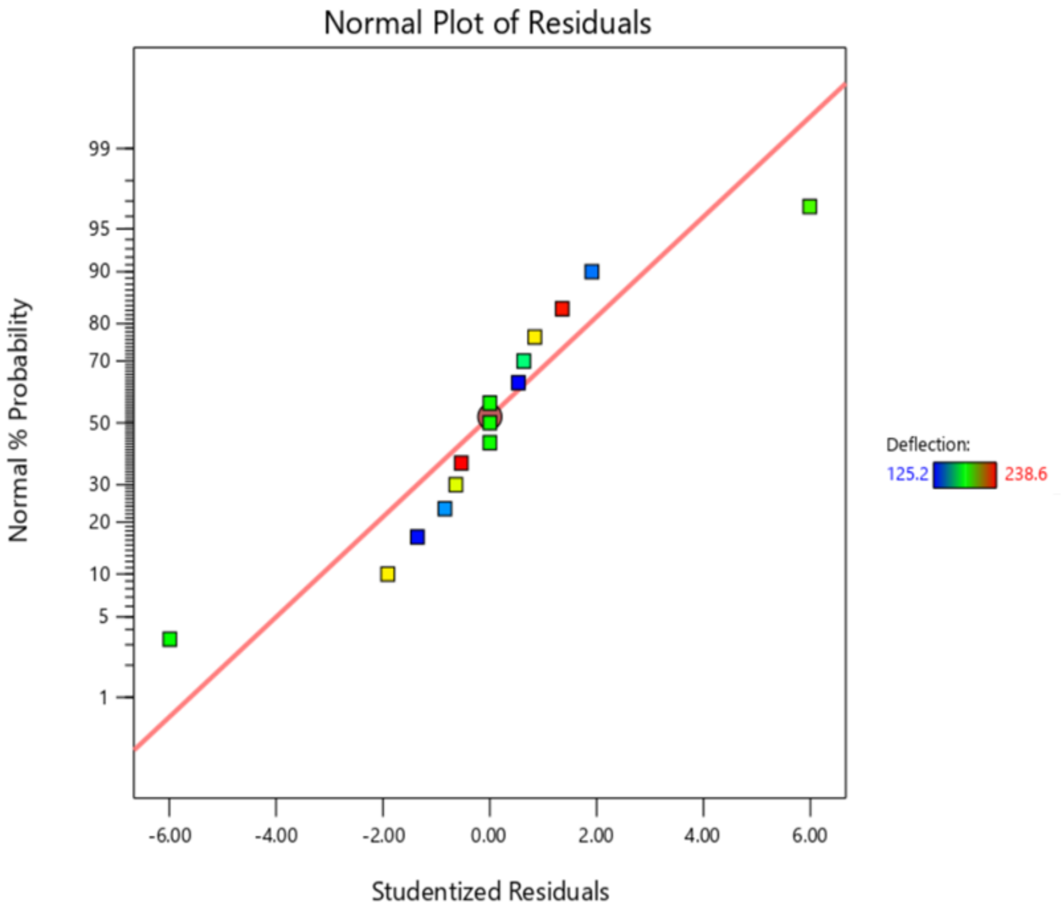

Figure 4.3 (a) Diagnostic plot: Normal Probability vs. Studentized Residual plot

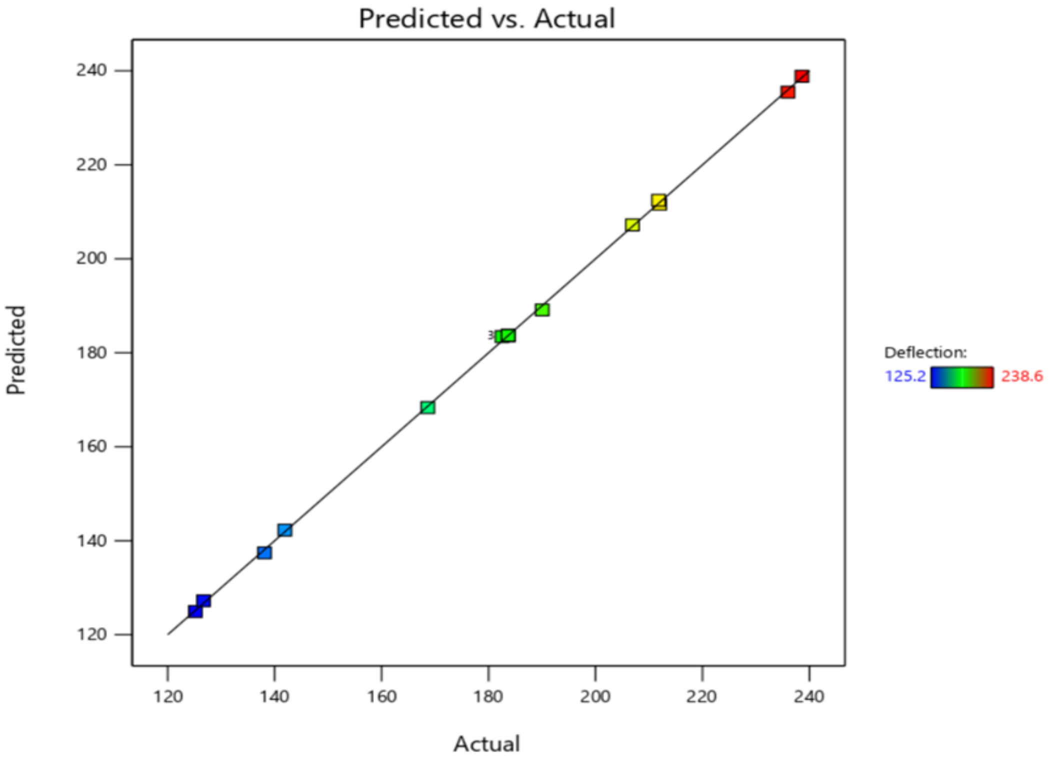

Figure 4.3 (b) Diagnostic plot: predicted vs. actual

4.2.2 Effect of Parameters on Response

4.2.2.1 Effect of individual parameters on response

The main effects plot address how the individual terms with respective levels affect the response. Here in Fig. 4.3, not a single term is parallel to horizontal axis that means all the terms with different levels respond to output. The parameter A and C show negative slope so their effect on response is negative but in case of term B which shows positive slope and their slope is steeper than other parameters. So this particular factor has higher impact in the main effects plot. As displayed in the Fig.4.4 vertical deflection of the node is increased sharply with the rise in beam length but the deflection decreases with the rise in concrete strength and beam depth.

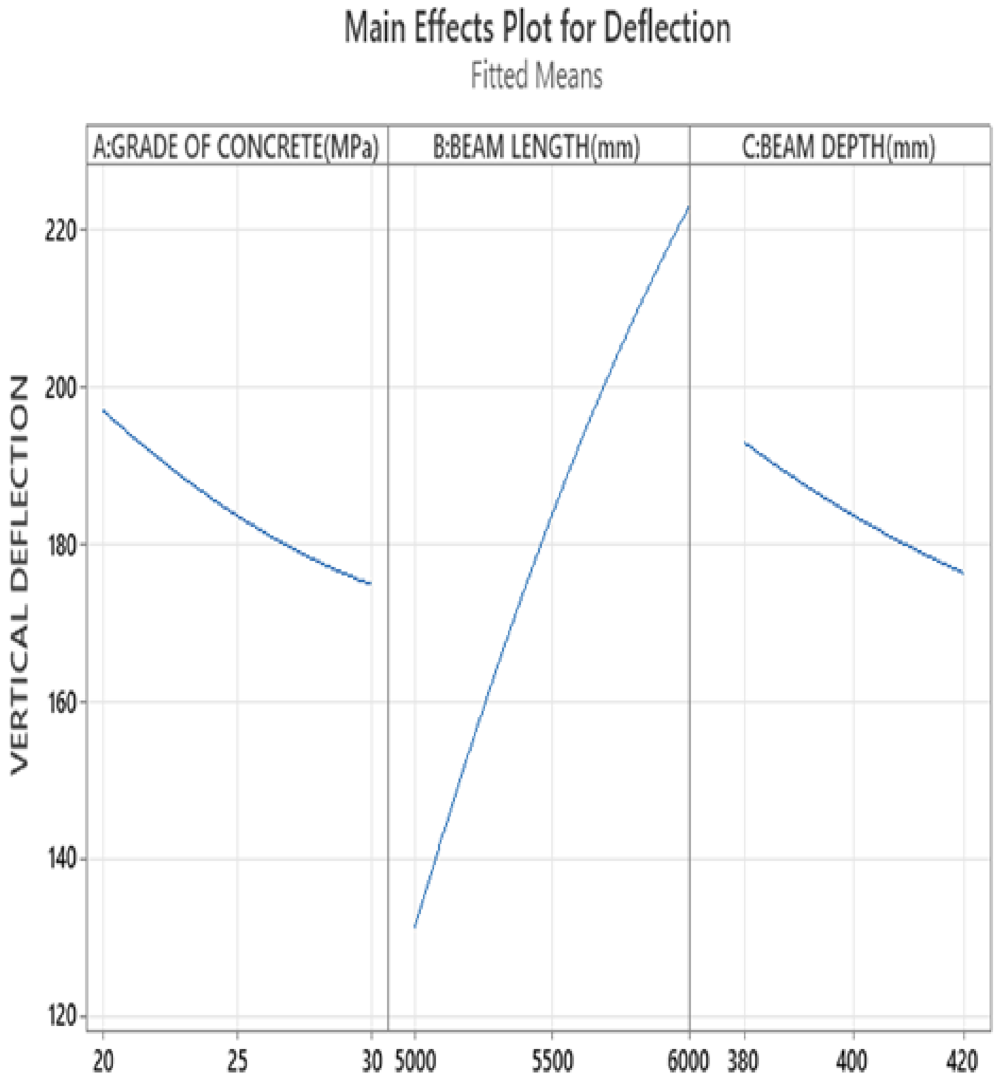

Figure 4.4 Main Effect Plot

4.2.3 Effect of interaction parameters on response

Three-dimensional (3-D) surface for the computed responses are generated based on the model equations to explain clearly the interaction effect of the parameters on the responses. Here two input variables are varied within experimental ranges and one is maintained at mid-range for each plotted surfaces. Fig. 4.5 (a) depicts the vertical deflection as a response with respect to interaction effect of grade of concrete and beam length while beam depth held at constant mid value of 400 mm.

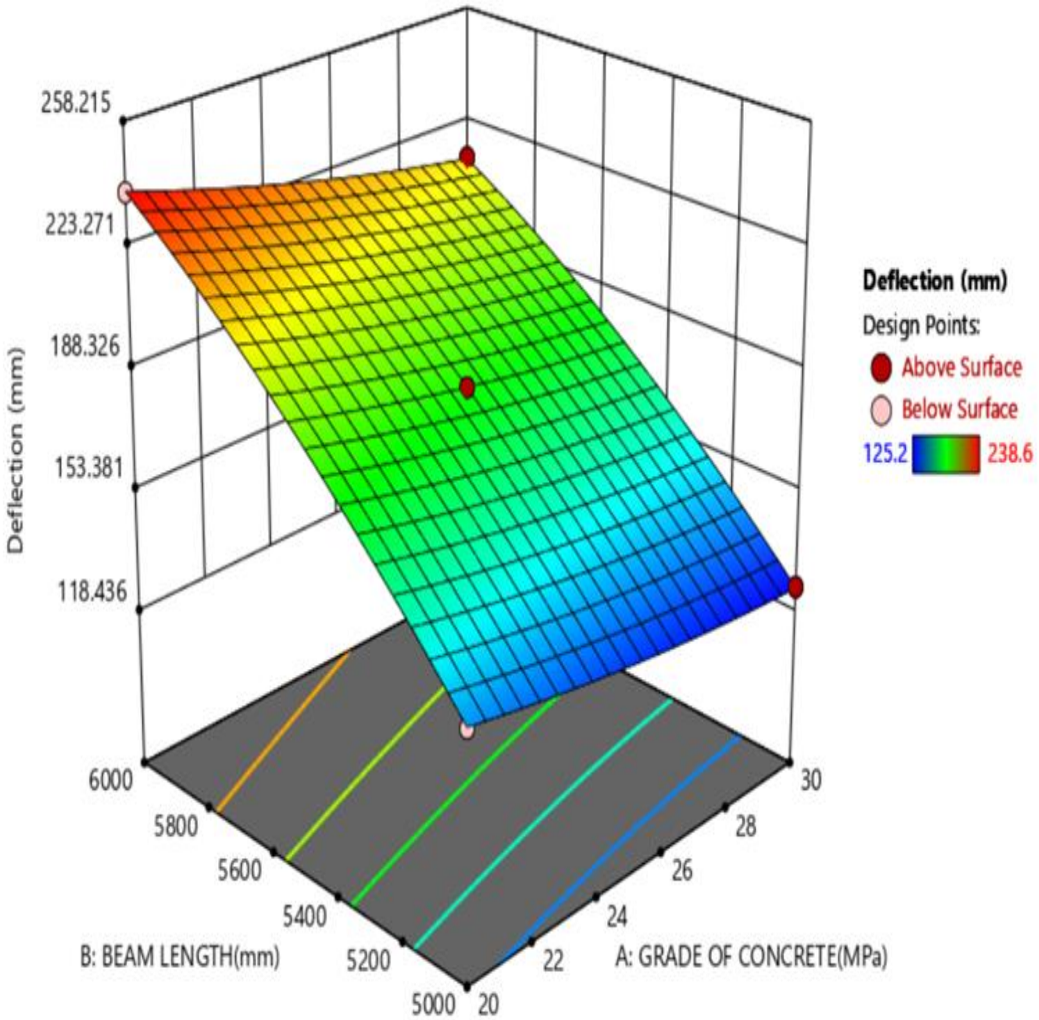

Figure 4.5 (a) 3D Surface of combined effect of beam length and grade of concrete on the deflection

Variation of the interaction effect of the parameters on the response can be seen by observing the effect of the beam length at different level of grade of concrete in the Fig.4.5 (a). At low grade of concrete, the vertical deflection increases with the increase in beam length. And at higher grade of concrete, the vertical deflection increases with the increase in beam length but the rate of increase is low which is attributed to interaction of the parameters.

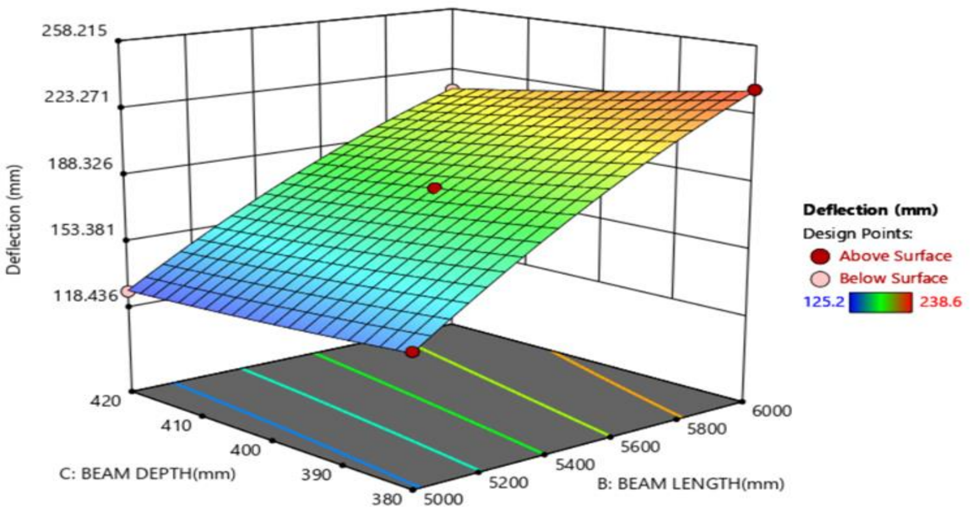

Figure 4.5 (b) 3D Surface of combined effect of beam depth and beam length on the deflection

Fig.4.5 (b) shows deflection of beam with respect to interaction effect of length and depth of beam while the grade of concrete is maintained at a constant mid-value of 25 MPa. As the beam depth increases, deflection of beam decreases. At lower value of beam depth and length, deflection is smaller as compared at higher value of both the terms.

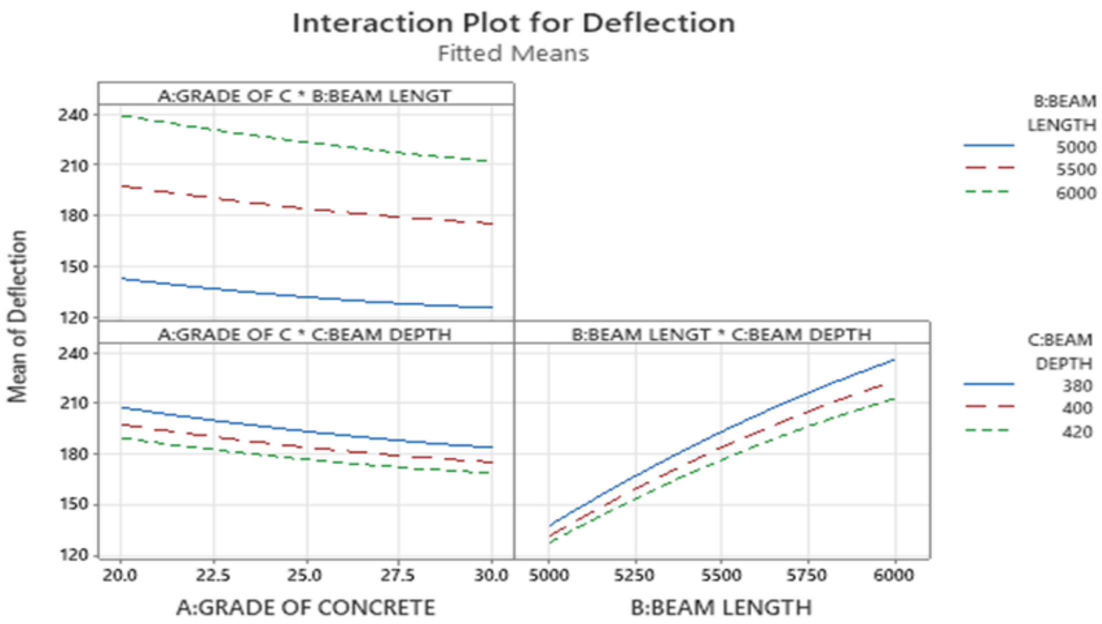

Figure 4.6 Interaction Plot in 2D

At a given beam length, the vertical deflection is higher at lower level of beam depth as compared to higher level of beam depth. The vertical deflection is higher at lower value of beam depth and concrete grade as compared to their higher values. This can be also be understood by observing the interaction plot shown in Fig. 4.6.

4.3 PENULTIMATE COLUMN REMOVAL CASE

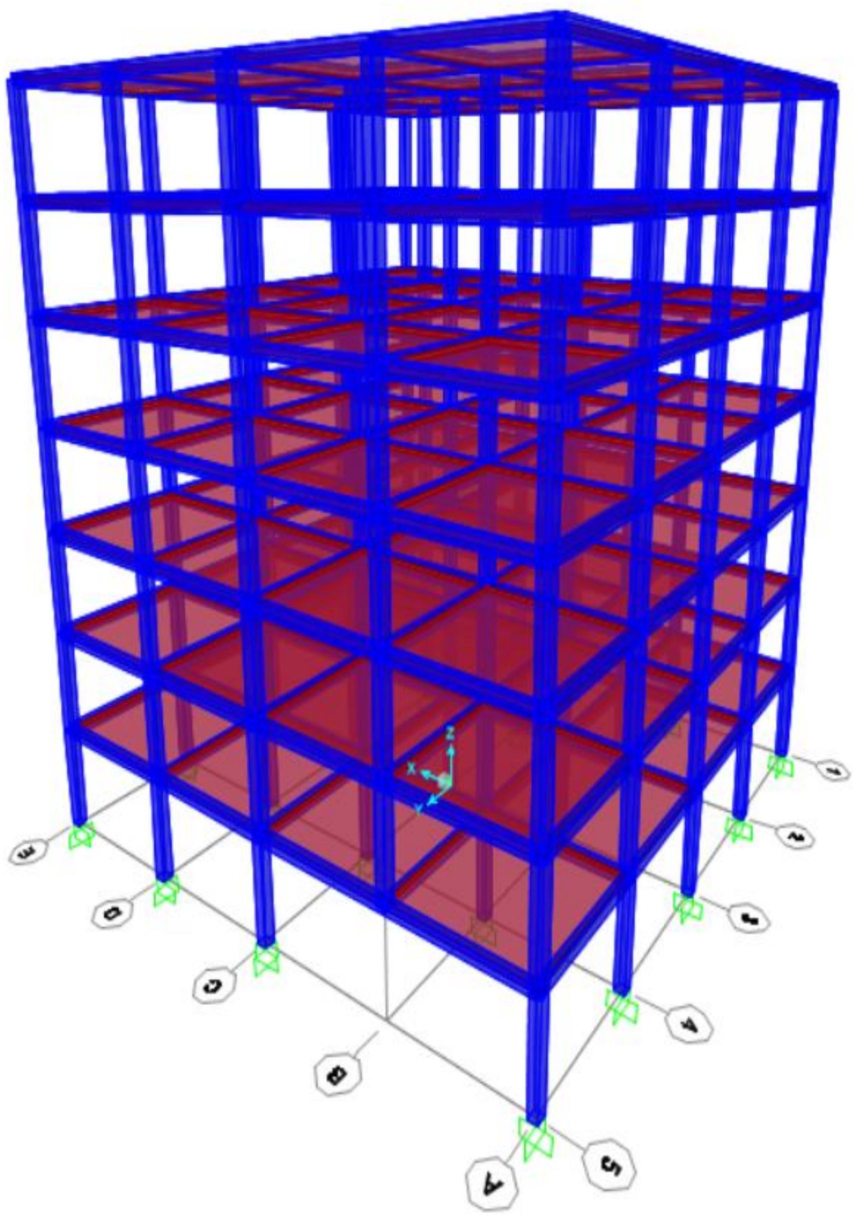

Figure 4.7 Penultimate Column (5B) Removal Case

Table 4.2 Analysis of variance - Penultimate Column

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6026.59	9	669.62	1087.90	< 0.0001	significant
A-GRADEOF CONCRETE (MPa)	401.15	1	401.15	651.74	< 0.0001	
B-BEAM LENGTH (mm)	5346.30	1	5346.30	8685.89	< 0.0001	
C-BEAM DEPTH (mm)	209.72	1	209.72	340.72	< 0.0001	
AB	2.13	1	2.13	3.46	0.1218	
AC	0.0156	1	0.0156	0.0254	0.8796	
BC	2.33	1	2.33	3.78	0.1095	
A^2	3.84	1	3.84	6.24	0.0546	
B^2	57.76	1	57.76	93.83	0.0002	
C^2	0.1747	1	0.1747	0.2838	0.6171	
Residual	3.08	5	0.6155			
Lack of Fit	3.08	3	1.03			
Pure Error	0.0000	2	0.0000			
Cor Total	6029.67	14				
R2	=0.9918					

Here Table 4.2 depicts ANOVA test result for quadratic model of the vertical deflection mentioned in equation (4.2). The p-value below 0.05 signifies the model accuracy as well as individual model terms at 95 % confidence interval. The model F-value of 1087.90 implies the model is significant. Having large F-value, there is only 0.01 % chance that it could happen as a result of noise. In this case A, B, C and B^2 are significant model terms whereas term A^2 is very close to be significance.

$$V.D. = -584.802 -1.60025 *A + 0.263522 *B - 0.256 *C - 0.000292 *AB -0.000625 * AC -7.625e-05 * BC + 0.0408 * A^2 -1.582e-05 *B^2 + 0.00054375 * C^2 \quad (4.2)$$

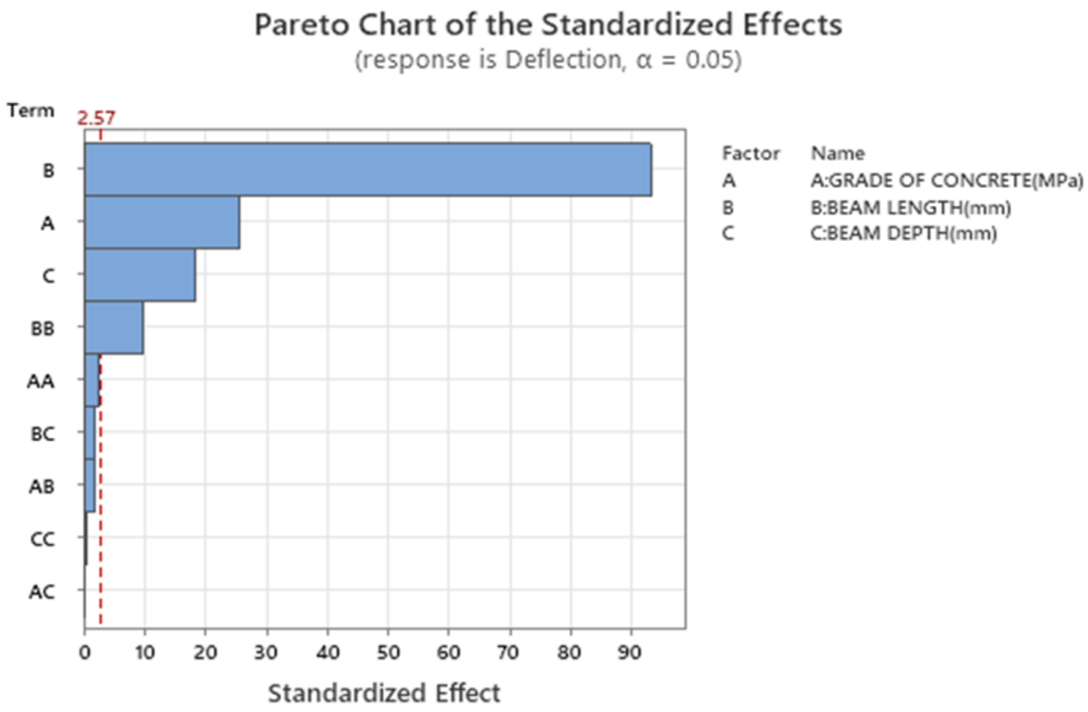

Figure 4.8 Pareto Chart

In Fig.4.8 Pareto chart described the significance and influence of different terms. From this chart it is clearly shown that factors A, B, C and B 2 crossed the reference line of 2.57 value that depict terms are statically significant at significance level of $\alpha = 0.05$ for the current model. The major effect caused by term B (beam length) followed by term A (grade of concrete), term C (beam depth) and term B^2. The terms A^2 is very close to significance point. The terms C^2, BC, AB and AC are could not cross the reference line and these terms are not significant.

4.3.1 Diagnostic Plots

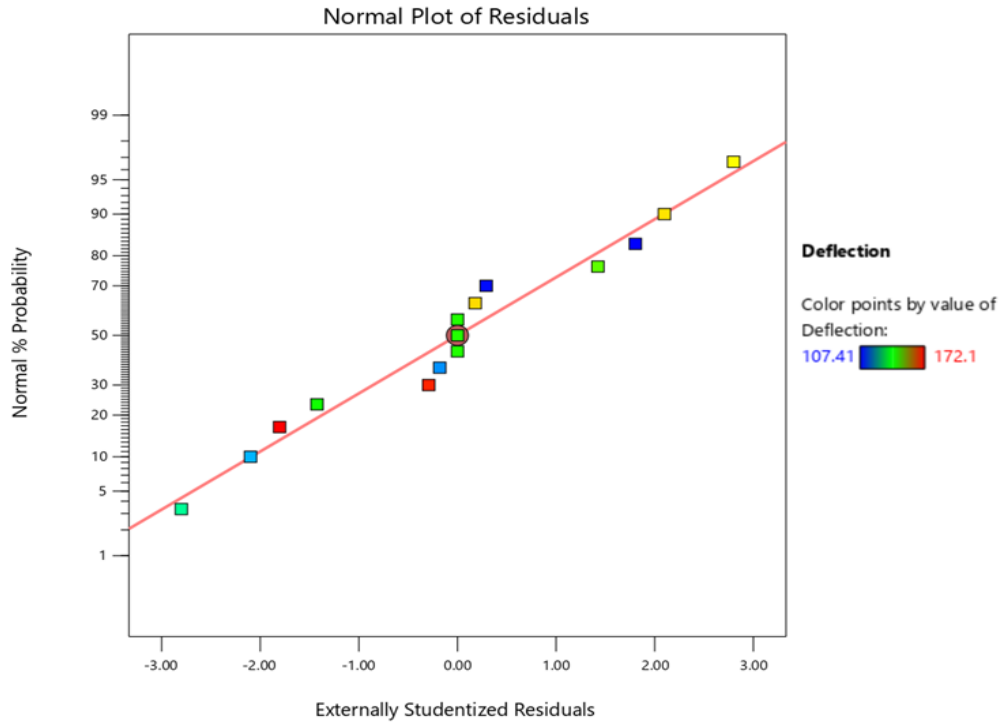

Figure 4.9. (a) Diagnostic plot: Normal Probability vs. Studentized Residual plot

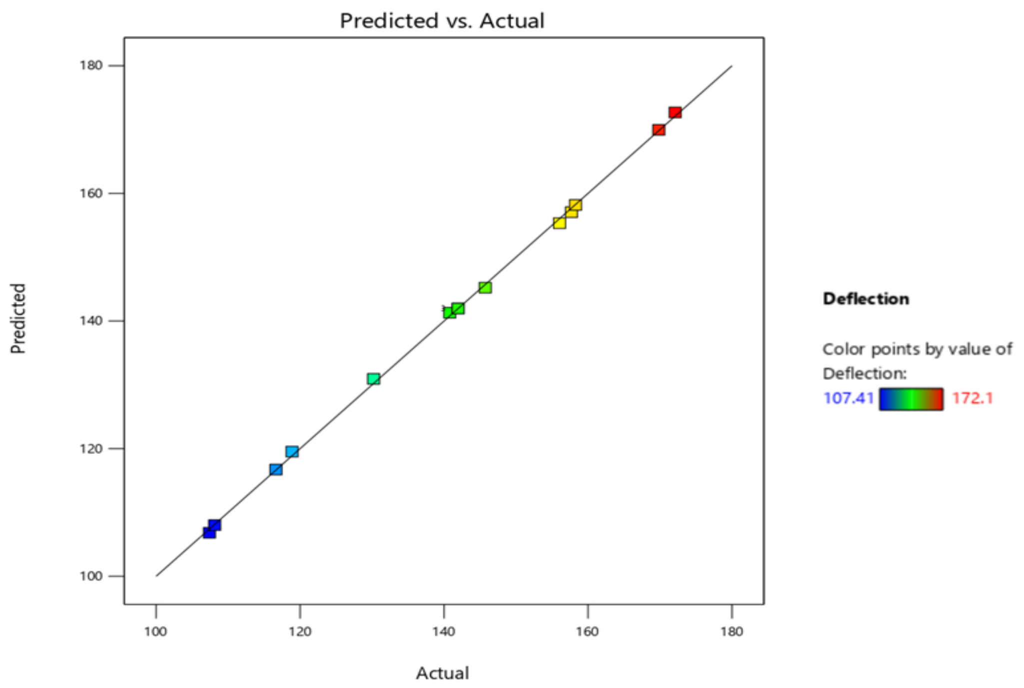

Figure 4.9 (b) Diagnostic plot: Actual versus Predicted plot8520/

The diagnostic plots like predicted vs. actual as well as normal probability vs. studentized residual plot give model adequacy. In Fig.4.9 (a) residuals depicts normal distribution pattern with little scattering along a straight line, as the data is normally distributed. Fig.4.9 (b) shows a strong correlation between the actual and anticipated values of beam deflection.

4.3.2 Effect of Parameters on Response:

4.3.2.1 Effect of individual parameters on response

The main effects plot shows the variation of different parameters. According to the Fig. 4.10 all the three parameters have influence on the response. Grade of concrete and beam depth follows similar trend and whereas beam length follows opposite trend.

The parameter A and C show negative slope so their effect on response is negative but in case of term B which shows positive slope and their slope is steeper than other parameters. So this particular factor has greater impact in the main effects plot. In the Fig. 4.10 vertical deflection of the column removal node is increased sharply with the rise in beam length but the deflection decreases with the rise in concrete strength and beam depth.

Figure 4.10. Main Effects Plot

4.1.3 Interaction Effect of Parameters on Response

Three-dimensional (3-D) surface for the computed responses are generated based on the model equations to better explain the interaction effect of parameters on the response. Here two input variables are varied within their ranges and one is maintained at mid-range for each plotted surfaces. Fig. 4.11 shows deflection as a response with respect to interaction effect of grade of concrete and beam length keeping beam depth at constant mid values of 400 mm. Variation of the interaction effect of the parameters on the response can be seen by observing the effect of the beam length at different level of grade of concrete in the figure. At low grade of concrete, the vertical deflection increases with the increase in beam length. And at higher grade of concrete, the vertical deflection increases with the increase in beam length but the rate of increase is low which is attributed to the interaction of beam length and grade of concrete.

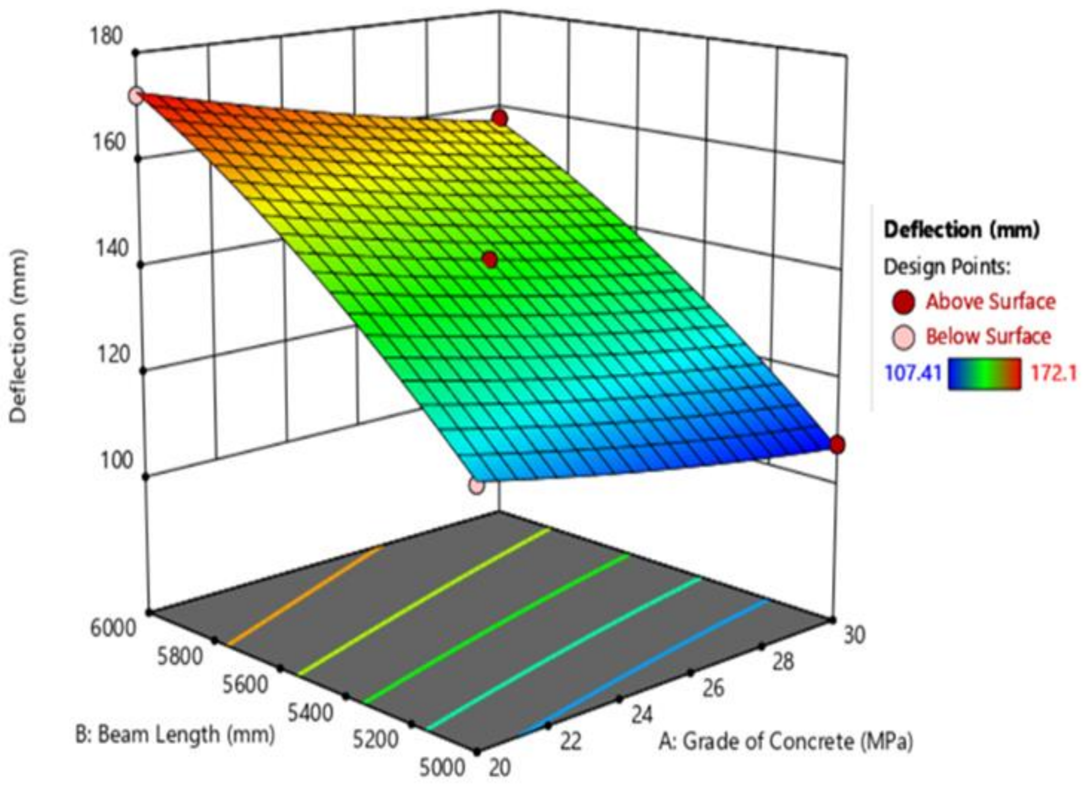

Figure 4.11 3D Surface of combined effect of beam length and grade of concrete on the deflection

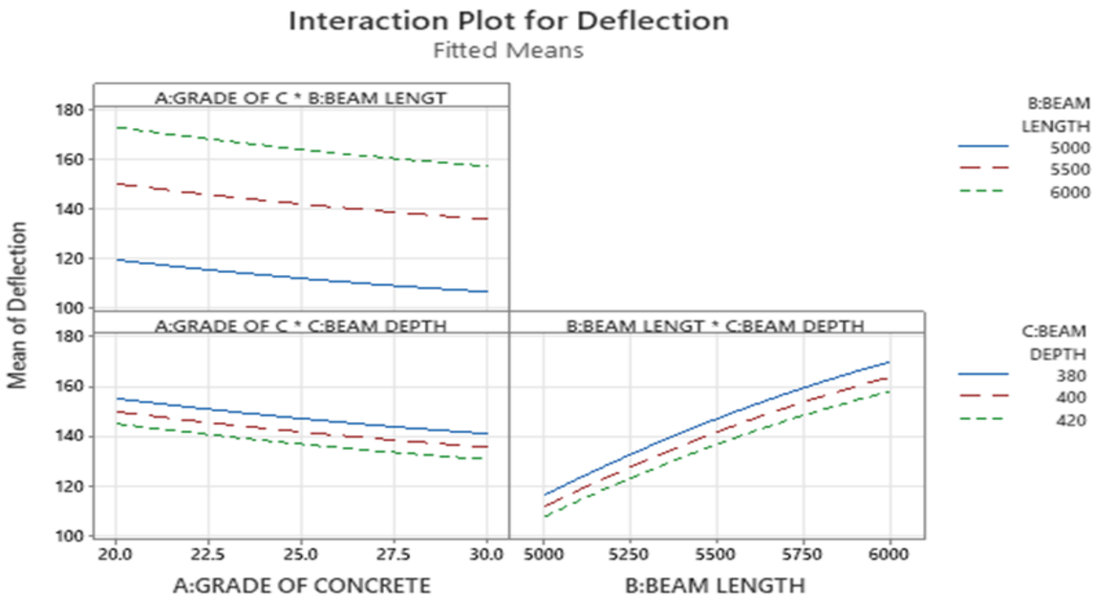

Figure 4.12 Interaction Plot in 2D

This can be also be understood by observing the interaction plot shown in Fig. 4.12.

4.4 MIDLLE COLUMN REMOVAL CASE

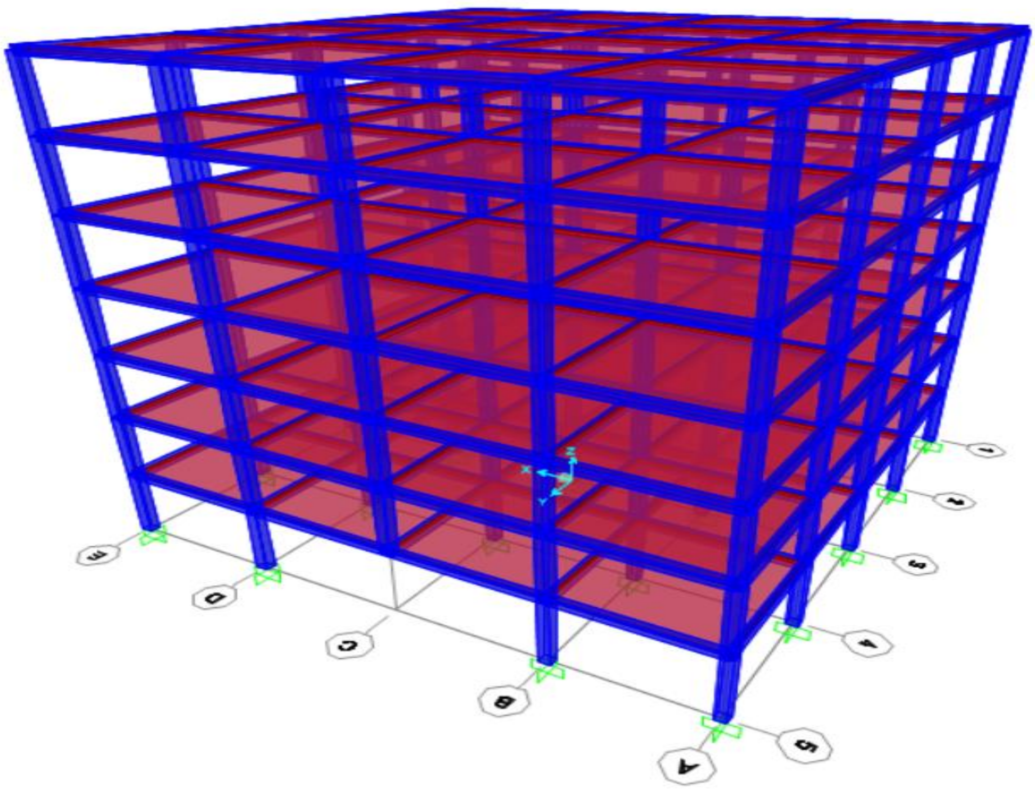

Figure 4.13 Midlle Column (5C) Removal Case

Table 4.3 Analysis of variance-Middle Column

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4720.00	9	524.44	1061.45	< 0.0001	significant
A-GRADE OF CONCRETE(MPa)	327.17	1	327.17	662.17	< 0.0001	
B-BEAM LENGTH(mm)	4102.82	1	4102.82	8303.88	< 0.0001	
C-BEAM DEPTH(mm)	191.98	1	191.98	388.56	< 0.0001	
AB	1.17	1	1.17	2.36	0.1850	
AC	0.0121	1	0.0121	0.0245	0.8818	
BC	2.45	1	2.45	4.96	0.0765	
A^2	2.66	1	2.66	5.38	0.0680	
B^2	88.07	1	88.07	178.24	< 0.0001	
C^2	0.1021	1	0.1021	0.2065	0.6685	
Residual	2.47	5	0.4941			
Lack of Fit	2.47	3	0.8235			
Pure Error	0.0000	2	0.0000			
Cor. Total	4722.47	14				
R^2	=0.9916					

Again, Table 4.3 shows ANOVA test result of quadratic model for the vertical deflection of the upper node caused by column removal as mentioned in equation (4.3). The p-value below 0.05 signifies the model accuracy as well as individual model terms at 95 % confidence interval. The Model F-value of 2775.42 implies the model is significant. Having large F-value, there is only 0.01 % chance that it could happen as a result of noise. In this case A, B, C, and B^2 are significant model terms whereas BC and A^2 are very close to significant. Because their values are more than 10%, the terms AB, AC, and C2 are not significant.

$$V.D. = - 692.794 -1.5685*A + 0.296877 * B - 0.133313 * C - 0.000216 * AB - 0.00055 * AC -7.825e-05 * BC + 0.03395 * A^2 -1.9535e-05 * B^2 + 0.000415625 * C^2 \quad (4.3)$$

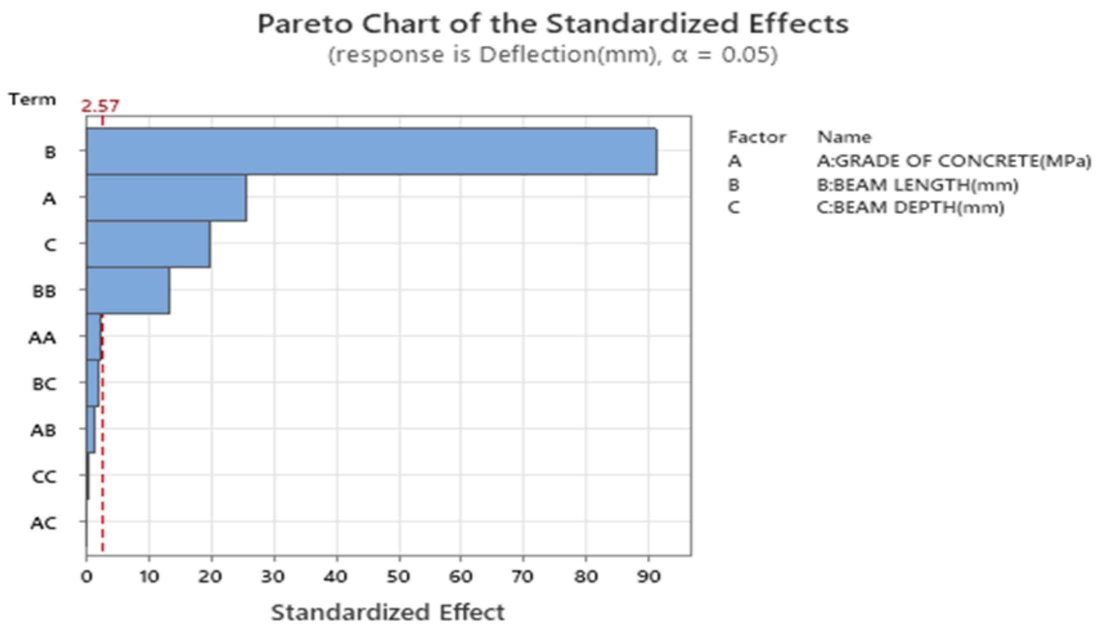

Figure 4.14 Pareto Chart

In Fig. 4.14 Pareto chart described the relevance and influence of different terms. From the above chart it is clearly shown that the terms A, B, C and B^2 is above the reference line of 2.57 value which indicate that the terms are statically significant at significance level of $\alpha = 0.05$ for the current model. The major effect caused by term B (beam length) followed by term A (grade of concrete), term C (beam depth) and term B^2. The terms A^2 and BC are close to the reference line. The terms AB, AC and C^2 are not significant terms.

4.4.1 Diagnostic Plots

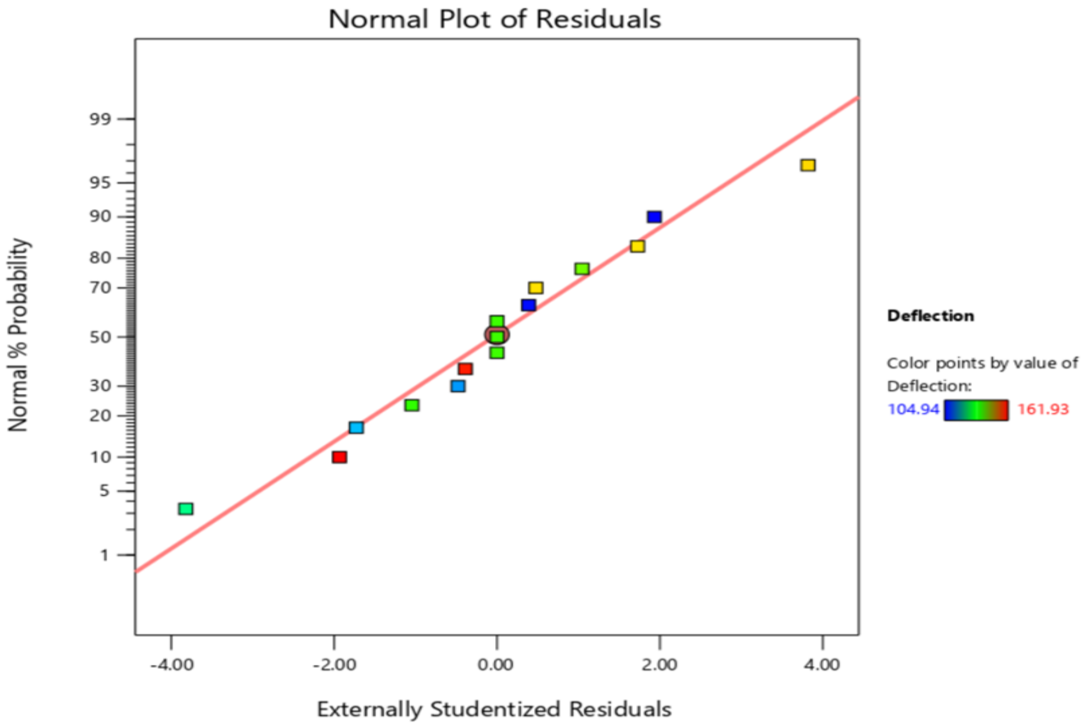

Figure.4.15 (a) Diagnostic plot: Normal Probability vs. Studentized Residual plot

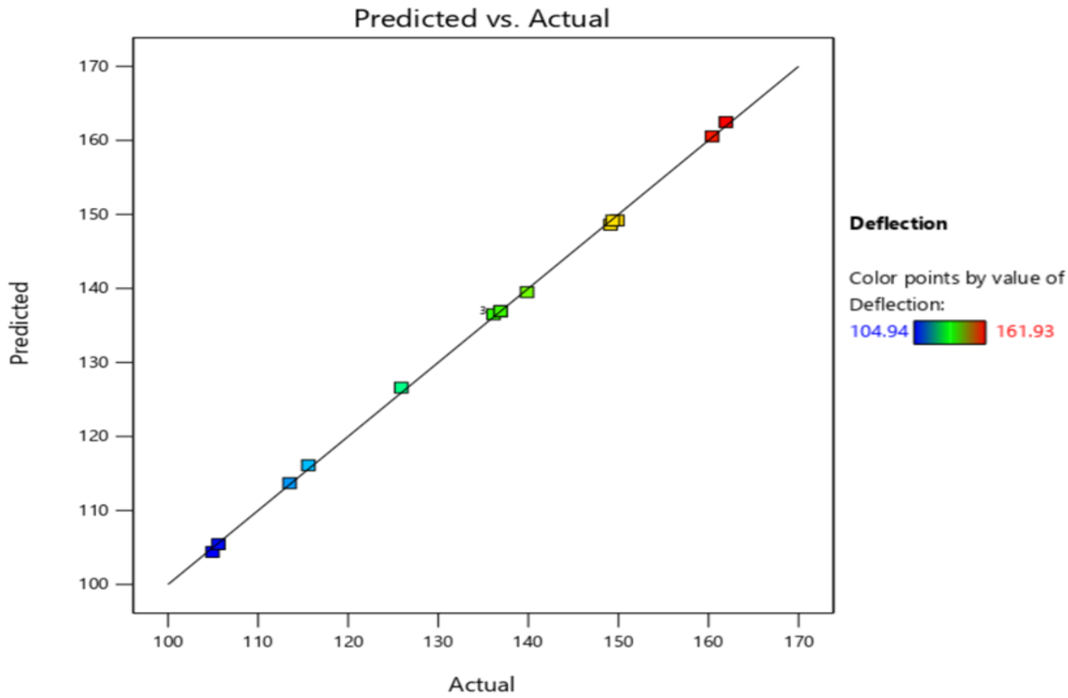

Figure 4.15 (b) Diagnostic plot: Actual versus Predicted plot

The diagnostic plots like predicted vs. actual as well as normal probability vs. studentized residual plot give model adequacy. Fig.4.15 (a) depicts normal distribution pattern with little scattering along a straight line, as the data is normally distributed. Fig.4.15 (b) shows a strong correlation between the actual and anticipated values of vertical deflection.

4.4.2 Effect of Parameters on Response

4.4.2.1 Effect of individual factors on response

The main effects plot tells about how the individual terms with their respective levels affect the response. Here in Fig.4.16, not a single term is parallel to horizontal axis that means all the terms with different levels respond to output. The parameter A and C show negative slope so their effect on response is negative but in case of term B which shows positive slope and their slope is steeper than other parameters. So this particular factor has higher impact in the main effects plot. The vertical deflection of the column removal node is increased sharply with the rise in beam length but the deflection decreases with the rise in concrete strength and beam depth.

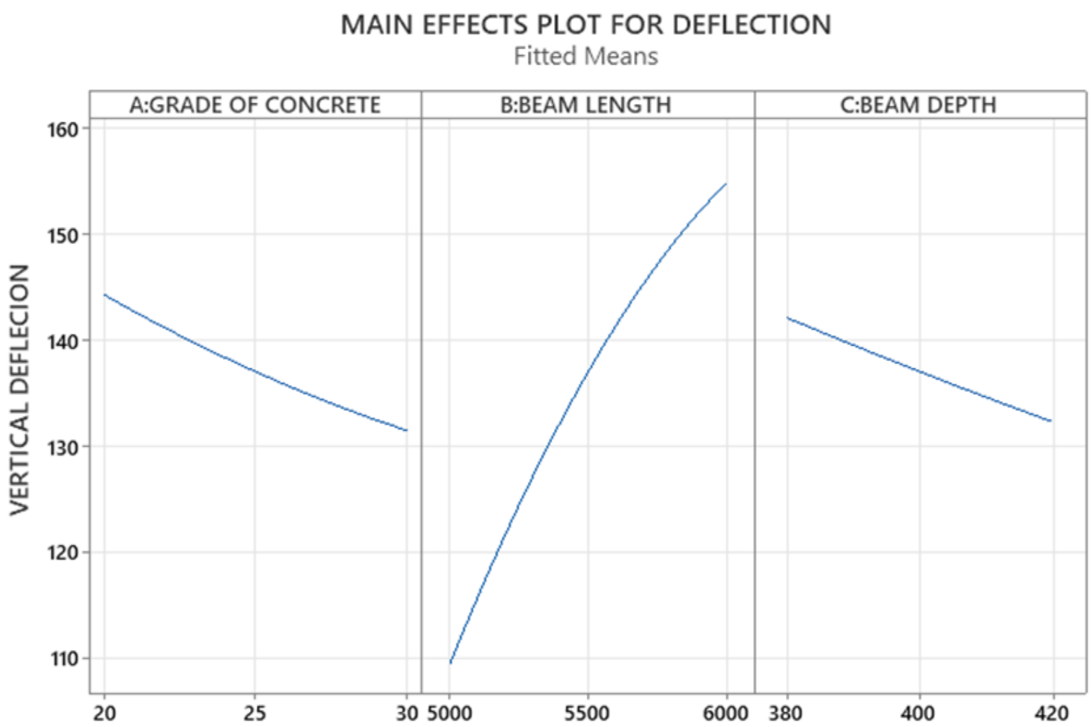

Figure 4.16 Main Effects Plot

4.4.2.2 Interaction Effect of parameters on response

Based on the model equations, three-dimensional (3-D) plots for the measured responses are generated to explain the combined effect of the parameters on the response. Here two input variables are varied within the range and one is maintained at mid-range for each plotted surfaces. Fig. 4.17 depicts the vertical deflection as a response with respect to combined effect of beam depth and beam length while grade of concrete held at constant mid value of 25 MPa. Variation of the combined effect of the parameters on the response can be seen by observing the effect of the beam length at different level of beam depth in the figure. At low beam depth, the vertical deflection increases with the increase in beam length. And at higher beam depth, the vertical deflection increases with the increase in beam length but the rate of increase is low which is attributed to interaction of the two varying parameters.

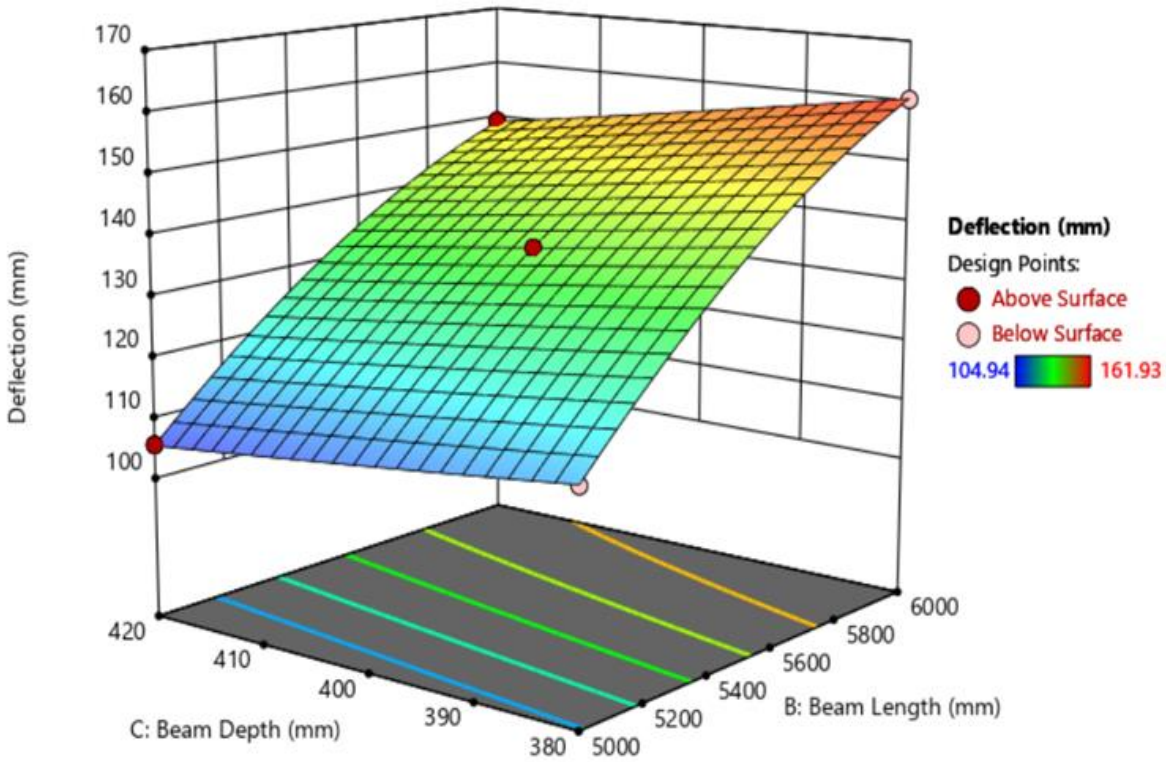

Figure 4.17 3D Surface of combined effect of beam depth and beam length on the deflection

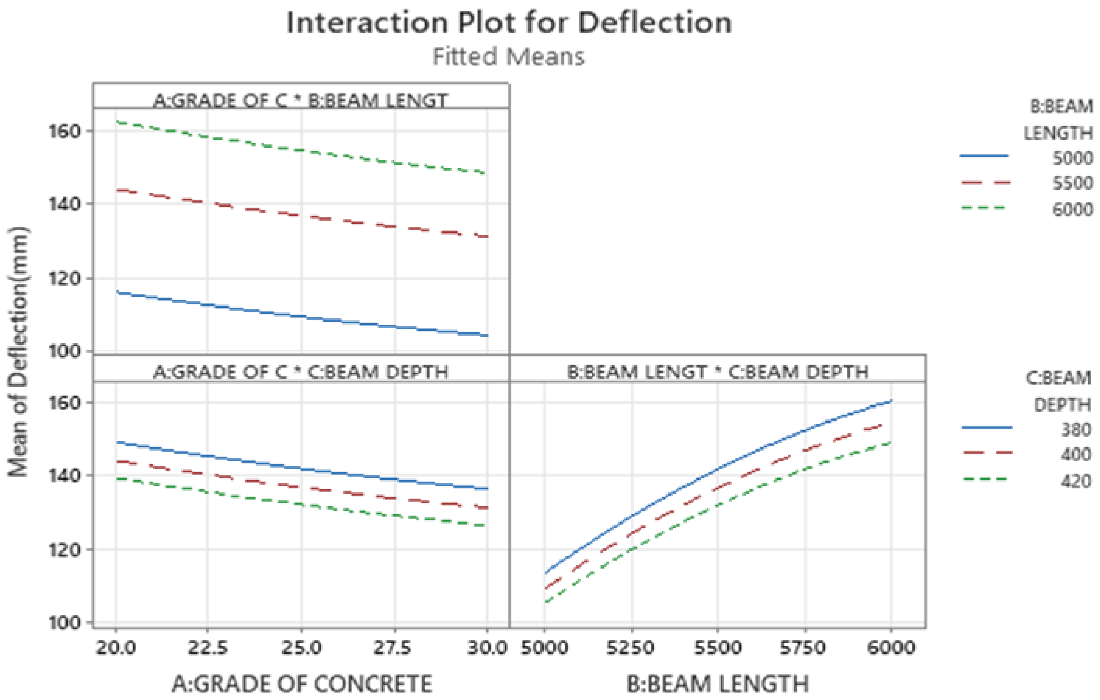

Figure 4.18 Interaction Plot in 2D

This can be also be understood by observing the interaction plot shown in Fig.4.18.

4.5 OPTIMAL RESPONSE

Table 4.4 Optimum value for all three case of column removal

Case	Factor: A (Grade of Concrete	Factor: B (Beam Length)	Factor: C (Beam Depth)	Optimum Value
Case 1: 5A	29.635	5012.108	408.878	124.839
Case 2: 5B	28.896	5005.075	405.706	106.919
Case 3 :5C	28.416	5011.523	409.745	104.539

In order to achieve minimum vertical deflection under progressive collapse analysis for the three column positions, the optimum values of the input factors are displayed in the above Table 4.4. Using regression equation (4.1), (4.2) and (4.3), the optimum values of different factors are obtained. The values of grade of concrete (A) and beam depth (C) should be in the higher range and beam length (B) should be in the lower range to get the optimal response.

4.6 SUMMARY OF THE CHAPTER

In this chapter mathematical models of beam response for all assumed cases have been generated, tested the adequacy of model, performed sensitivity analysis of influential parameters and discussed about simulation based results. The main effects plot and Pareto charts have been discussed to check the significance of input factors and its magnitude of standardised effect. This chapter also includes optimisation of the parameters.

CHAPTER-5

CONCLUSION

5.1 GENERAL

In the current research, beam behaviour is analysed under nonlinear dynamic approach of progressive collapse for three different cases of column removal position. Box–Behnken design of RSM has been utilised for generation of second order polynomial for the vertical deflection. Main effects and two way interactions have been addressed to check the performance of beam under disproportionate collapse.

5.2 CONCLUSION

The following conclusions can be drawn

1) RSM fits a polynomial quadratic model for the vertical deflection with a 95 per cent confidence interval for all considered cases. In the elimination cases of corner column, middle column, and penultimate corner column, the coefficient of determination R^2 values are 99.68 %, 99.16 %, and 99.18 %, respectively.
2) Based on ANOVA results, all three input parameters have substantial impact on the response in each of the three positions of column elimination.
3) The main effects plots for each case are non-horizontal line that describes the significance of individual factors with different levels on the response.
4) Based on the Pareto chart, maximum standardised effect of different terms in the descending orders are beam length, grade of concrete and beam depth with 5% significance level for all three cases.
5) The interaction effect of different factors, grade of concrete with beam length, beam depth with beam length are significant in corner column elimination. But in middle column elimination case, the interaction effect of beam length and depth is close to significant while no interaction effects are found significant in penultimate column removal case.

6) In corner column elimination, at low grade of concrete, the vertical deflection rises with the rise in beam length. And at higher grade of concrete, the vertical deflection rises as the beam length rises but the rate of increase is low. At lower value of beam depth and length, deflection is smaller as compared at higher value of both the terms.
7) The values of grade of concrete and beam depth should be in the higher range and beam length should be in the lower range to get the optimal response.

5.3 LIMITATIONS AND FUTURE PROSPECTS

The current study employs nonlinear dynamic analysis and does not consider threat dependent cases. It focuses on middle column, penultimate column and corner column elimination at ground floor level only.

For future research, more cases of column removal can be taken at different floor level of a building. For prediction analysis of beam behaviour, other machine learning techniques like artificial neural network, support vector machine algorithm etc. can be used.

REFERENCE

[1] ASCE 7 (2010), “Minimum design loads for buildings and other structures”, American Society of Civil Engineers, Reston, VA, USA.

[2] NIST, (2007) “Best Practices for Reducing the Potential for Progressive Collapse in Buildings,” National Institute of Standards and Technology Report No. NISTIR 7396, USA.

[3] GSA. (2013) “Alternate path analysis and design guidelines for progressive collapse resistance”, General services and administration.

[4] Marjanishvili, Shalva, (2004), “Progressive Analysis Procedure for Progressive Collapse”. Journal of Performance of Constructed Facilities– J.Perform.Constr.Facil.18.10.1061/(ASCE)0887-3828(2004)18:2(79).

[5] Adam, J. M., Parisi, F., Sagaseta, J. and Lu, X. (2018), “Research and practice on progressive collapse and robustness of building structures in the 21st century,” Engineering Structures, vol. 173. Elsevier Ltd, pp. 122–149, Oct. 15, 2018, doi: 10.1016/j.engstruct.2018.06.082.

[6] Griffiths, H., Pugsley, A. G., and Saunders, O. (1968). “Report of the inquiry into the collapse of flats at Ronan Point, Canning Town.” Her Majesty’s Stationery Office, London.

[7] Hinman, E. E., and Hammond, D. J. (1997). “Lessons.from the Oklahoma City bombing”, ASCE, New York.

[8] Dailymail, (2001), http://www.dailymail.co.uk/news/article-2040657/Explosions-caused-jet-fuel-water-sprinklers-brought-TwinTowers-9-11-scientists-say.html

[9] Xiao-Huang-Can He, Wei-Jian Yi, Xian-Xun Yuan, (2019). “A non-iterative progressive collapse design method for RC structures based on virtual thermal pushdown analysis”, Engineering Structures, Volume 189, Pages 484-496, ISSN 0141- 0296, https://doi.org/10.1016/j.engstruct.2019.03.102

[10] Lim, N. S., Tan, K. H. & Lee, C. K., (2018), "A simplified model for alternate load path assessment in RC structures". Engineering Structures, 171, 696-711. doi: 10.1016/j.engstruct.2018.05.074.

[11] Tsai, Meng-Hao & Lin, Bing-Hui. (2009). "Dynamic amplification factor for progressive collapse resistance analysis of an RC building". The Structural Design of Tall and Special Buildings. 18. 539 - 557. 10.1002/tal.453.

[12] Mohajeri Nav F, Usefi N, Abbasnia R. (2018), "Analytical investigation of reinforced concrete frames under middle column removal scenario". Advances in Structural Engineering;21(9):1388-1401. doi:10.1177/1369433217746343.

[13] Elsanadedy, Hussein & Al-Salloum, Yousef & Almusallam, Tarek & Ngo, Tuan & Abbas, H. (2019), "Assessment of progressive collapse potential of special moment resisting RC frames – Experimental and FE study". Engineering Failure Analysis. 105. 10.1016/j.engfailanal.2019.07.045.

[14] Gombeda, Matthew J. & Naito, Clay & Quiel, Spencer & Fallon, Corey, (2016), "Blast-Induced Damage Mapping Framework for Use in Threat-Dependent Progressive Collapse Assessment of Building Frames". Journal of Performance of Constructed Facilities. 31. 04016089. 10.1061/(ASCE)CF.1943-5509.0000949.

[15] De-Cheng Feng, Si-Cong Xie, Wen-Ni Deng, Zhao-Dong Ding, (2019), "Probabilistic failure analysis of reinforced concrete beam-column sub-assemblage under column removal scenario". Engineering Failure Analysis, Volume100, Pages 381-392, ISSN 1350-6307, https://doi.org/10.1016/j.engfailanal.2019.02.004.

[16] Azim, I., Yang, J., Iqbal, M.F., (2021), "Prediction of Catenary Action Capacity of RC Beam- Column Substructures under a Missing Column Scenario Using Evolutionary Algorithm". KSCE J CivEng 25, 891–905. https://doi.org/10.1007/s12205- 021-0431-0.

[17] Li Shan, Floriana Petrone, Sashi Kunnath, (2019), "Robustness of RC buildings to progressive collapse: Influence of building height". EngineeringStructures,Volume183,Pages690-701,ISSN0141-0296,https://doi.org/10.1016/j.engstruct. 2019.01.052.

[18] Li Y, Lu X, Guan H, Ren P, Qian L, (2016), “Probability-based progressive collapse-resistant assessment for reinforced concrete frame structures”. Advances in Structural Engineering;19(11):1723-1735. doi:10.1177/1369433216649385.

[19] Feng, De-Cheng & Sicong, Xie & Xu, Jun & Kai, Qian. (2019). “Robustness quantification of reinforced concrete structures subjected to progressive collapse via the probability density evolution method”. Engineering Structures. 202. 109877. 10.1016/j.engstruct. 109877. (2019).

[20] Sasani, Mehrdad, (2008), “Response of a reinforced concrete infilled-frame structure to removal of two adjacent columns”. Engineering Structures - ENG STRUCT. 30. 2478-2491. 10.1016/j.engstruct.2008.01.019.

[21] Adam, Jose & Buitrago, Manuel & Bertolesi, Elisa & Sagaseta, Juan, (2020), “Dynamic performance of a real-scale reinforced concrete building test under a corner-column failure scenario”. Engineering Structures. 210. 10.1016/j.engstruct.2020.110414.

[22] Pham, Tuan, & Lim, Namyo & Tan, Kang-Hai. (2017), “Investigations of tensile membrane action in beam-slab systems under progressive collapse subject to different loading configurations and boundary conditions”. Engineering Structures. 150. 520-536. 10.1016/j.engstruct.2017.07.060.

[23] Kai, Qian & Li, Bing, (2017), “Dynamic and residual behavior of reinforced concrete floors following instantaneous removal of a column”. Engineering Structures. 148. 175–184. 10.1016/j.engstruct.2017.06.059.

[24] Yu, Jun & Tang, Jian-Hui & Luo, Li-Zhong & Fang, Qin, (2020), “Effect of boundary conditions on progressive collapse resistance of RC beam-slab assemblies under edge column removal scenario”. Engineering Structures. 225. 111272. 10.1016/j.engstruct.2020.111272.

[25] Sadek F, Joseph A. Main,H. S. Lew, Yihai Bao, (2011), “Testing and analysis of steel and concrete beam-column assemblies under a column removal scenario”. J.Struct.Eng.;137(9):881-92.

[26] Joshi, D.D., Patel, P.V., (2019), “Experimental study of precast dry connections constructed away from beam–column junction under progressive collapse

scenario. Asian J.Civ. Eng. 20, 209–222 (2019). https://doi.org/10.1007/s42107-018-0099-z.

[27] Namyo Salim Lim, K.H. Tan, C.K. Lee, (2017), “Experimental studies of 3D RC substructures under exterior and corner column removal scenarios”. Engineering Structures, Volume 150, , Pages 409-427, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2017.07.041.

[28] Naghavi, F., Tavakoli, H.R. (2021), “Probabilistic Prediction of Failure in Columns of a Steel Structure Under Progressive Collapse Using Response Surface and Artifcial Neural Network Methods”. Iranian Journal of Science and Technology, Transactions of Civil Engineering https://doi.org/10.1007/s40996-021-00593-z.

[29] Massimo Aria, Corrado Cuccurullo. (2017), “Bibliometrix: An R-tool for comprehensive science mapping analysis, Journal of Informetrics, Volume 11, Issue 4, 2017, Pages 959-975, ISSN 1751-1577, https://doi.org/10.1016/j.joi.2017.08.007.

[30] Van Eck, N.J., Waltman, L. (2017), “Software survey: VOSviewer, a computer program for bibliometric mapping”. Scientometrics 84, 523–538 (2010). https://doi.org/10.1007/s11192-009-0146-3.

[31] Kessler, M., (2017)."An experimental study of bibliographic coupling between technical papers” (Corresp.)," in IEEE Transactions on Information Theory, vol. 9, no. 1, pp. 49-51, January 1963, doi: 10.1109/TIT.1963.1057800.

[32] Walter, Christian & Ribiere, Vincent. (2013). “A citation and co-citation analysis of 10 years of KM theory and practices”. Knowledge Management Research & Practice. 11. 10.1057/kmrp.2013.25.

[33] Haleem, Abid & Khan, Mohd Imran & Khan, Shahbaz & Jami, Abdur Rahman, (2020). “Research status in Halal: a review and bibliometric analysis”. Modern Supply Chain Research and Applications. ahead-of-print. 10.1108/MSCRA-06-2019- 0014.

[34] Song, Yu & Chen, Xieling & Hao, Tianyong & Zhinan, Liu & Lan, Zixin. (2019). “Exploring two decades of research on classroom dialogue by using bibliometric analysis”. Computers & Education. 137. 10.1016/j.compedu.2019.04.002.

[35] Esfahani, Hossein & Tavasoli, Keyvan & Jabbarzadeh, Armin. (2019), “Big data and social media: A scientometrics analysis”. International Journal of Data and Network Science. 145-164. 10.5267/j.ijdns.2019.2.007.

[36] Marjanishvili S., Agnew E. (2006) “Comparison of various procedures for progressive collapse analysis”. J Perform Constr Facil 2006;20(4).

[37] Karmoker, J.R.; Hasan, I.; Ahmed, N.; Saifuddin, M.; Reza, M.S. (2019). "Development and Optimization of Acyclovir Loaded Mucoadhesive Microspheres by Box -Behnken Design".Dhaka University Journal of Pharmaceutical Sciences. 18 (1): 1–12. doi:10.3329/dujps.v18i1.41421.

[38] Chang, K., (2015). “e-Design Computer-Aided Engineering Design”, Pg.579