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Examining The Impact Of The Knowledge Factor On Structural Retrofitting Cost

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Abstract: The retrofitting of existing structures is one of the most challenging problems in the field of engineering. Retrofitting is one of the most important steps in assuring the safety of an existing structure. The major challenge in earthquake-vulnerable buildings which occurs at the time of retrofitting is the amount of available information in obtaining sufficient records of buildings such as architectural and structural drawings, foundation details, design calculations, geotechnical reports, material properties and records of at least natural period of the buildings in order to evaluate the current condition of the building structures.
According to Indian Standards, the quantity of information accessible at the retrofitting stage is expressed by knowledge factor K. The knowledge factor is a very sensitive metric, and material strength is directly related to it. Residential structures were examined by taking into account all of the various knowledge factors provided by the Indian Standard code in order to discover the link between structural retrofitting cost and knowledge factor. When the knowledge factor was reduced from 1 to 0.7, there was no significant increase in structural element failure, but when the knowledge factor was reduced from 0.7 to 0.5, a sharp curve was detected.
To summarise the financial effect, numerous retrofit alternatives are developed to meet varying seismic safety requirements. The structural retrofit costs are estimated and summed to assess the impact. The research examines the effect of knowledge factor on the structural retrofitting cost and it was found the structural retrofitting cost skyrocketed with the decrease in the knowledge factor.

Key words: Structural retrofitting, knowledge factor, seismic analysis of structures, glass fibre wrapping, micro-concreting, shear walls.

Introduction

Concrete building degradation is a global issue as a result of earthquakes, a lack of understanding of codes and inadequate supervision quality. An earthquake has a significant impact on buildings, and in certain circumstances, they are damaged to the ground level [1]. In construction sector, one of the most important demand of recent time is the retrofitting of existing structures in seismic prone areas. The aim of these interventions involves enhancing building's capacity to become bigger than the demand induced by a severe earthquake [2]. In order to quantify the seismic retrofit, methods based on new materials, such as Fibre Reinforced Polymers (FRPs), jacketing by steel or concrete, installation of shear walls, and techniques based on new materials, such as Fibre Reinforced Polymers (FRPs) have been adopted.

Different retrofit interventions are implemented and their cost are evaluated after the assessment of building performance through pushover analysis. With regard to the retrofitting cost evaluation of existing structures, several aspects might impact the final conclusion. The structure's knowledge levels (KL) can be a very sensitive metric that governs the amount of assistance required. The amount of in-situ tests performed on existing buildings is used to define knowledge levels [3].

Knowledge Factor (As defined by IS 15988:2013), a factor to represent the uncertainty about the reliability of the available information about the structural configuration and present condition of materials and components of the existing building. The high expense of new construction and the historical significance of older buildings, many individual house owners and big companies, including government organisations, have chosen to repair/retrofit rather than replace existing structures [4]. The knowledge level will have indirect impact on the retrofitting strategy and consequently, the choice of retrofitting strategies adopted will have a significant impact on the retrofitting cost. The aim of this paper is to simulate the building and assess the effect of knowledge factor on retrofitting cost of a building.

The study will focus on evaluating the impact of knowledge factor on the structural retrofitting cost. In this research, simulation will be performed on the residential (high rise) building model to analyse the impact of retrofitting cost pertaining to different knowledge levels.

Literature review

Structural Audit

Seismic retrofitting of earthquake-prone structures is a modern issue with significant political and societal implications [5]. The structures should be audited on a regular basis for the protection of human life as well as the neighbouring structures [6]. A structural audit is a thorough examination of a building's overall health and function [7]. The process of retrofitting first start with the structural audits. The structural audit is divided into two steps: Preliminary Evaluation and Detailed Evaluation.

Knowledge Factor

The structural engineer's problems in earthquake-vulnerable buildings are obtaining sufficient records of buildings such as architectural and structural drawings, structural design calculations, material properties, details of foundation and geotechnical reports, records of at least natural period of the buildings in order to evaluate the increased stiffness of buildings because strengthening techniques most often stiffen the structure, reducing its natural stiffness. IS 15988:2013 defines the knowledge factor as a factor to represent the uncertainty about the reliability of the available information about the structural configuration and present condition of materials and components of the existing building. The strength capacity of the existing building components shall be based on the probable material strengths in the building. Through series of sampling and field or lab tests, probable or measured nominal strengths are obtained which are true indicator of actual strength. Probable strengths can be either measured by actual testing or by the values given in the original building documents. [8] defines that the following elements determine the level of knowledge:

- Geometrical properties of the structural system;
- Detailing of reinforcement for reinforced concrete, connections between steel components, connections between floors and wind bracing systems, characteristics of mortar in masonry joints, and so on;
- Materials: actual material properties

Determination and Incorporation in the Design

However, probable strengths must all be further changed to account for the uncertainty in the trustworthiness of accessible information as well as the component's current state. As per IS 15988:2013, to account for uncertainty, knowledge factor k must be multiplied by likely material strengths.

Table 1: Knowledge Factor, K [9]

Sl. No. (1)	**Description of Building** (2)	***K*** (3)
i)	Original construction documents available, including post-construction activities, such as modification to structure or materials testing undertaken of existing structure.	1.00
ii)	Documentation as in SI No. (i) but no testing of materials, that is using originally specified values for materials and minor deterioration of original condition	0.90
iii)	Documentation as in Si No. (i) no testing of, that is originally specified values for materials and minor deterioration of original condition	0.80
iv)	Incomplete but useable original construction documents and no testing	0.70
v)	Incomplete or no documents available but extensive testing and inspection done to establish current strength of load resisting members	0.70
vi)	Documentation as in SI No. (iv) and limited inspection, and verification of structural members, or materials test results with large variation	0.60
vii)	Little knowledge of details of a component	0.50

Some intrusive testing may be required to assess material quality as well as to confirm geometry and reinforcement provision conformity with the designs [8]. The number of in-situ tests performed on existing buildings is used to define the knowledge levels [10]. European code 8 part 3 explains determination of the knowledge level.

A study [10] examined an old reinforced concrete school building in Avellino, Italy, performing seismic analysis and vulnerability indices. The researchers suggested retrofitting techniques, including foundation system, deficient columns, beams, and shear wall addition. The total cost of retrofitting, including in-situ tests, was found to be half that of Knowledge Level 1 and 95% for Knowledge Level 3.

A study by [8] explores the importance of knowledge level in seismic analysis of existing buildings, using a school building in the Marche area. The knowledge level is divided into three levels according to the Italian Code (OPCM 3274): Limited Knowledge (KL1), Normal Knowledge (KL2), and Full Knowledge (KL3). The research highlights the need for refined testing methodologies to minimize overestimation of structural element quality and suggests further improvement for structural experts.

Retrofitting Techniques

Seismic retrofitting techniques of many types have been developed and deployed in practice. The fundamental ideas of these retrofitting procedures are targeted towards (a) enhancement of the structure's lateral strength (b) enhancement of the structure's ductility (c) enhancement of strength and ductility. The choice to repair and reinforce a structure is influenced not only by the technical reasons described above, but also by a cost/benefit analysis of the various possibilities.

The alteration of existing structures to make them more resistant to seismic activity, ground motion, or soil failure caused by earthquakes is known as seismic retrofitting [11]. To obtain the required solution for an existing building various retrofitting approaches, namely global and local retrofitting techniques, are used. The retrofitting techniques are defined in the IS 15988:2013 and in other research papers [4] [5] [11] [12].

Seismic retrofitting is crucial for concrete structures susceptible to damage and failure due to seismic forces. The choice of retrofitting technique depends on load, deformation, and energy dissipation parameters.

Knowledge level indirectly influences the choice of retrofitting technique, making it essential to recognize and carry out the ideal retrofitting in a cost-effective manner.

Data Collection

Case study 1

The case study is located in Sector 88, Faridabad. The case study building is a residential project. The Apartment are of the following configurations: 2BHK, 3BHK and 4BHK. The project is spread over a total area of 6.13 acres of land. The project has a total of 6 towers of 14 floors each.

Case study 2

The project is a ready-to-move housing society in Sector-15, Bahadurgarh. It provides flats and individual floors in a variety of price ranges. This property offers 1BHK, 2BHK, 3BHK, and 5BHK apartments, as well as 3BHK independent floors. The project proposal has seven high rise structures with G+13 storeys.

The case study is in the Bahadurgarh region, covering an area of 20 acres. The construction is designed for being earthquake resistant R.C.C. framed with infill brickwork.

Analysis

Structural modelling, Seismic analysis and Design

The structural modelling, analysis and design of the case study buildings using E-TABS Ultimate C 19.0.0. Response spectrum analysis is performed on the structures to obtain the various parameters including the seismic weight, base shear, storey stiffness, storey drift, moments and forces at supports. The loads are then transferred to the Excel sheets for analysis and design of foundation for different case studies.

Response spectrum analysis is performed on the various cases on all the case studies. The following parameters are checked and compared to assess the difference in the performance with respect to different knowledge factors.

Base Shear

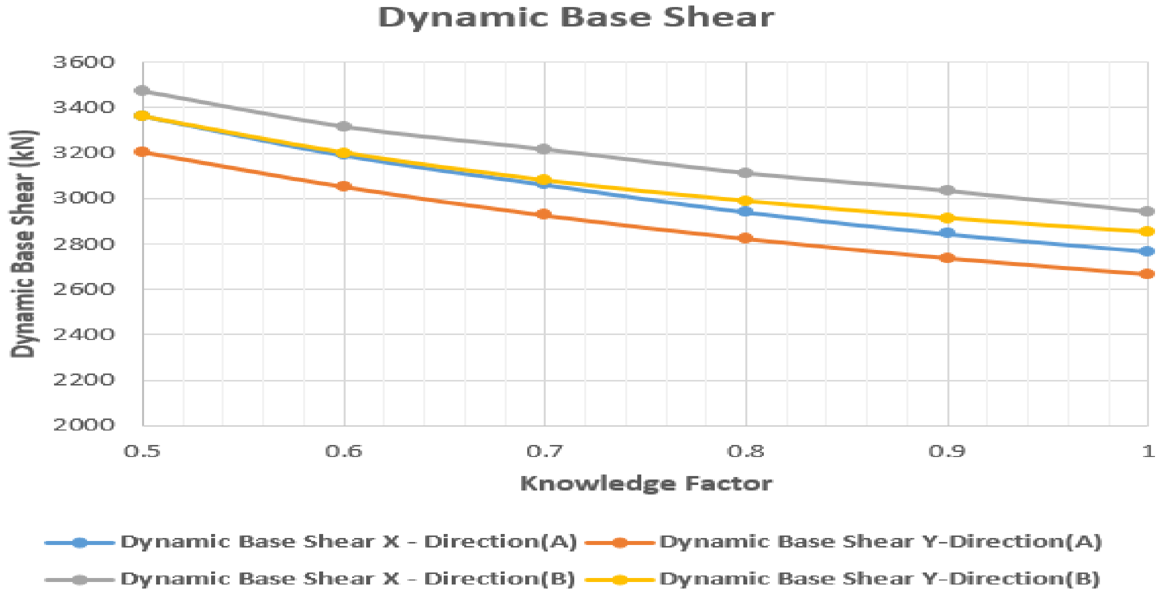
Base Shear is an estimate of the maximum expected lateral force that will occur due to seismic ground motion at the base of the structure. The dynamic base shear is noted for and compared with the base shear of the models with different knowledge factor in table 2.

Table 2: Comparison of Dynamic Base Shear (Different Knowledge Factor), (Source: Author)

K Factor	Dynamic Base Shear (kN)			
	Case Study I		Case Study II	
	X-Direction (A)	Y-Direction (A)	X-Direction (B)	Y-Direction (B)
1	2768	2666	2941	2850
0.9	2845	2738	3034	2912
0.8	2940	2823	3111	2987
0.7	3062	2926	3216	3078
0.6	3190	3053	3315	3201
0.5	3362	3206	3471	3361

Comparing the model, there was significant change in the dynamic base shear with respect to different case studies and no change was observed in the static base shear in respect to knowledge factor. It was noted from graph 1 that dynamic base shear increases with decrease in the knowledge factor.

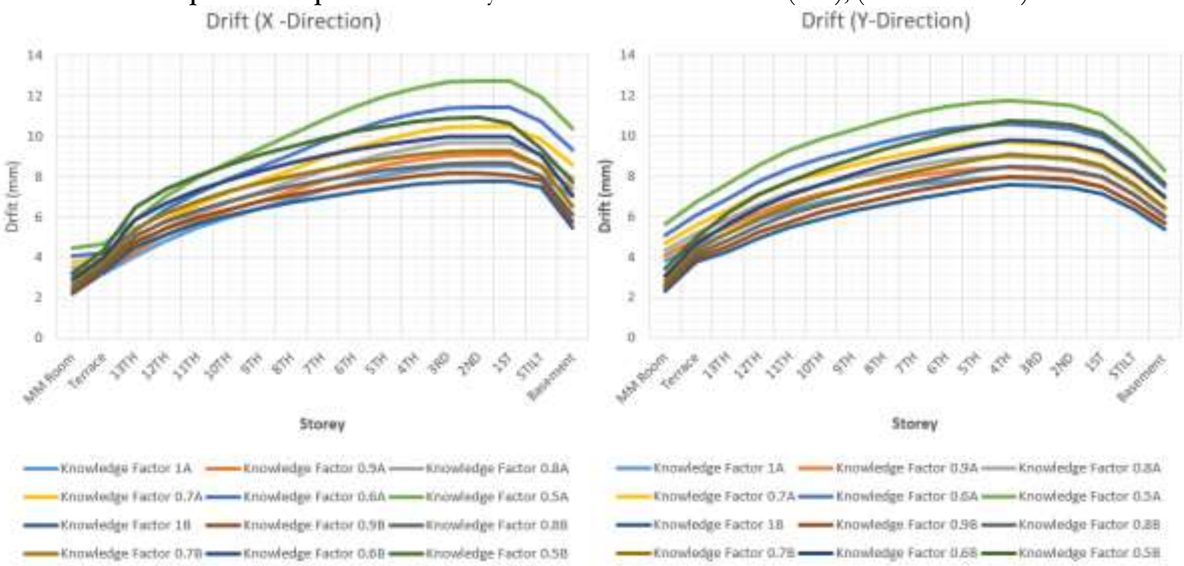
Graph 1: Dynamic Base Shear, (Source: Author)



Inter-storey Drift

Inter-storey drift is one of the particularly useful engineering response quantity and indicator structural performance, especially for high rise buildings. Inter-storey drift is the difference between the roof and floor displacements of any given storey as the building sways during the earthquake, normalized by the storey height. The inter-storey drift for the models are analysed for earthquake load cases in x-direction and y-direction & response spectrum load cases in x-direction and y-direction.

Graph 2 & Graph 3: Inter-storey Drift in X- & Y- Direction (mm), (Source: Author)

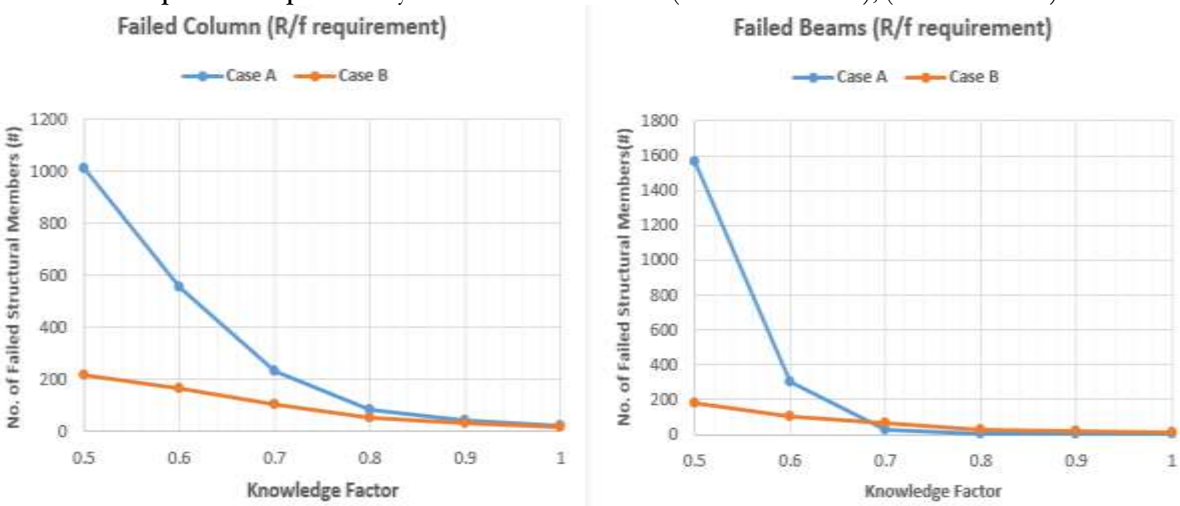


Comparing the results from the all the model cases from graph 2 and 3, it was observed that the inter-storey drift is higher for the lower floors in both x- and y- direction. This is because storey drift gradually increases with decrease in the knowledge factor in respect of all the storey.

Analysis of Structural Elements

The model cases were analysed based on different checking parameters like mass participation ratios, base shear, inter-storey drifts, story forces, etc. As per the analysis, some of the structural members failed due to reinforcing requirement is more as per the cross-section/ maximum allowed and some failed due to shear stress exceeds maximum allowed.

Graph 4 & Graph 5: Analysis of structural elements (Beams & Column), (Source: Author)



It was observed from graph 4 and graph 5 that number of structural elements (beams/columns) are failing due to shear stress which exceed the maximum allowed or due to reinforcement required exceeds the maximum allowed. The increased in the requirement of reinforcement and increase in the shear stress (due to shear force & torsion) is due to the decrease in the material strength of the elements. The material strength of the elements is hindered by the amount of availability of information at the time of retrofitting (Knowledge Factor).

Cost of retrofitting

After the structural analysis, the beams and columns that required retrofitting are identified. The retrofitting technique is then selected for each case study and the quantities are calculated accordingly. The required quantities are calculated only after understanding the sub activities in each retrofitting technique. The rates of items of work are taken and mentioned in table 3 and 4 as per the Delhi Schedule of Rates 2021 and non-schedule items are taken as per Market Rate Analysis.

Table 3: Cost of Items of Work for Glass Fibre Wrapping (Case A), (Source: Author)

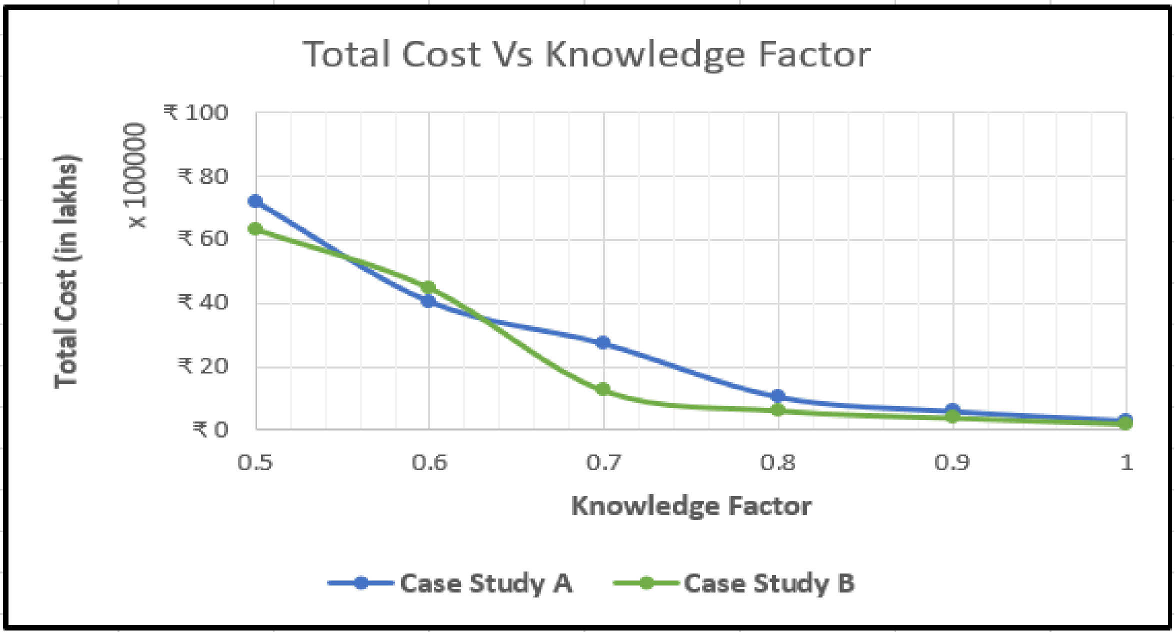
Case Study A	**Items of Work**			
Knowledge Factor	**Surface Preparation**	**Applying Epoxy Primer**	**Applying Epoxy Putty**	**Glass Fibre Wrapping**
1	17,843	43,716	38,185	2,14,121
0.9	34,412	84,310	73,643	4,12,949
0.8	60,291	1,47,714	1,29,024	7,23,497
0.7	1,55,392	3,80,711	3,32,539	18,64,706
0.6	2,30,415	5,64,517	4,93,088	27,64,979
0.5	4,09,358	10,02,296	8,76,025	49,12,292

Table 4: Cost of Items of Work for Glass Fibre Wrapping (Case B), (Source: Author)

Case Study B	**Items of Work**			
Knowledge Factor	**Surface Preparation**	**Applying Epoxy Primer**	**Applying Epoxy Putty**	**Glass Fibre Wrapping**
1	13,361	32,734	28,592	1,60,328
0.9	25,976	63,642	55,589	3,11,714
0.8	41,123	1,00,751	88,003	4,93,475
0.7	82,608	2,02,390	1,76,781	9,91,296
0.6	2,53,610	6,21,343	5,42,724	30,43,314
0.5	3,58,980	8,79,500	7,68,217	43,07,756

The graph 6 represents the variation of total cost of retrofitting using Fibre Reinforced Wrapping technique with respect to knowledge factor for both the case studies.

Graph 6: Total Cost of Retrofitting Vs Knowledge Factor, (Source: Author)



From the above graph 6, it can be noted that total cost of retrofitting increases with the decrease in the knowledge factor. The graph also concludes that huge variation and steep upward curve is observed when the knowledge factor moves from 0.7 to 0.6 in comparison to 0.8 and 0.9. The major reason for this type of variation is that as the whole system comprises of interlinked elements and failure of some members leads to sudden increase in load on other members which ultimately results in increase in the number of members failing due to requirement of excess reinforcement. The above summarizes that there is huge variation in cost in the items (surface preparation and fibre wrapping) as more number of columns and beams failed when the knowledge factor moves from 1 to 0.5.

The cost of retrofitting using micro-concreting techniques is summarized below in table 5 and 6 to analyse the effect of knowledge factor.

Table 5: Cost of Items of Work for Micro-concreting (Case A), (Source: Author)

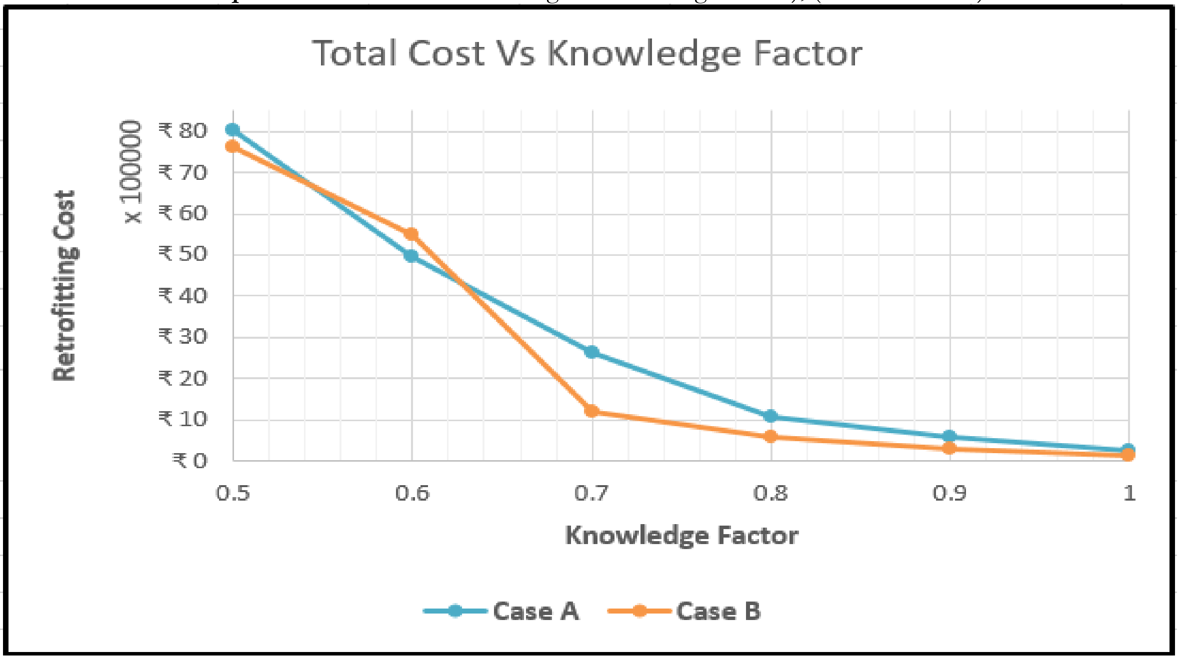
Case A	**Items of Work**			
Knowledge Factor	**Surface Preparation (Including dismantling and demolition)**	**Laying of reinforcement**	**Application of bonding agents**	**Micro-concreting (including protection plaster)**
1	1,12,021	3,442	37,427	89,717
0.9	2,70,051	16,582	90,225	2,16,282
0.8	4,73,137	22,566	1,58,077	4,20,714
0.7	12,19,440	30,300	4,07,419	9,76,640
0.6	23,04,104	50,670	7,69,809	18,45,339
0.5	36,94,804	1,21,352	12,34,446	29,59,139

Table 6: Cost of Items of Work for Micro-concreting (Case B), (Source: Author)

Case A	**Items of Work**			
Knowledge Factor	**Surface Preparation (Including dismantling and demolition)**	**Laying of reinforcement**	**Application of bonding agents**	**Micro-concreting (including protection plaster)**
1	71,950	2,211	24,039	57,624
0.9	1,39,222	4,278	46,514	1,11,502
0.8	2,75,627	5,904	92,088	2,20,748
0.7	5,54,881	15,214	1,85,388	4,44,400
0.6	25,47,287	32,738	8,51,057	20,40,102
0.5	35,36,187	50,497	11,81,450	28,32,100

The graph below (7) represents the variation of total cost of retrofitting using Micro-concreting technique with respect to knowledge factor for both the case studies. From the graph, it can be easily interpreted that there was steady increase in the total cost when knowledge factor decreases from 1 to 0.7 and steep slopes can be observed when knowledge factor decreases from thereon. The steep slopes depicts that there is huge rate of increase of retrofitting cost increases from rapidly when knowledge factor moves from 0.7 to 0.5. This represents if the amount of available information (drawings, testing reports, detail drawings etc.) is less for a particular building project, the cost of retrofitting will be more due to hindrance in the knowledge factor, hence hindering the material strength.

Graph 7: Total Cost of Retrofitting Vs Knowledge Factor), (Source: Author)



The shear walls are majorly constructed at different places on the outer periphery of the structure system. The shear walls are easily installed at the periphery of the structure; as it will not cause alteration in the appearance and windows layout. Addition of shear walls are generally not preferred at the interior of the structure. The quantities are estimated and cost is calculated for each of the wall in the system and then compared with the other systems in table 7 and 8.

Table 7: Cost of Items of Work for Addition of Shear Wall (Case B), (Source: Author)

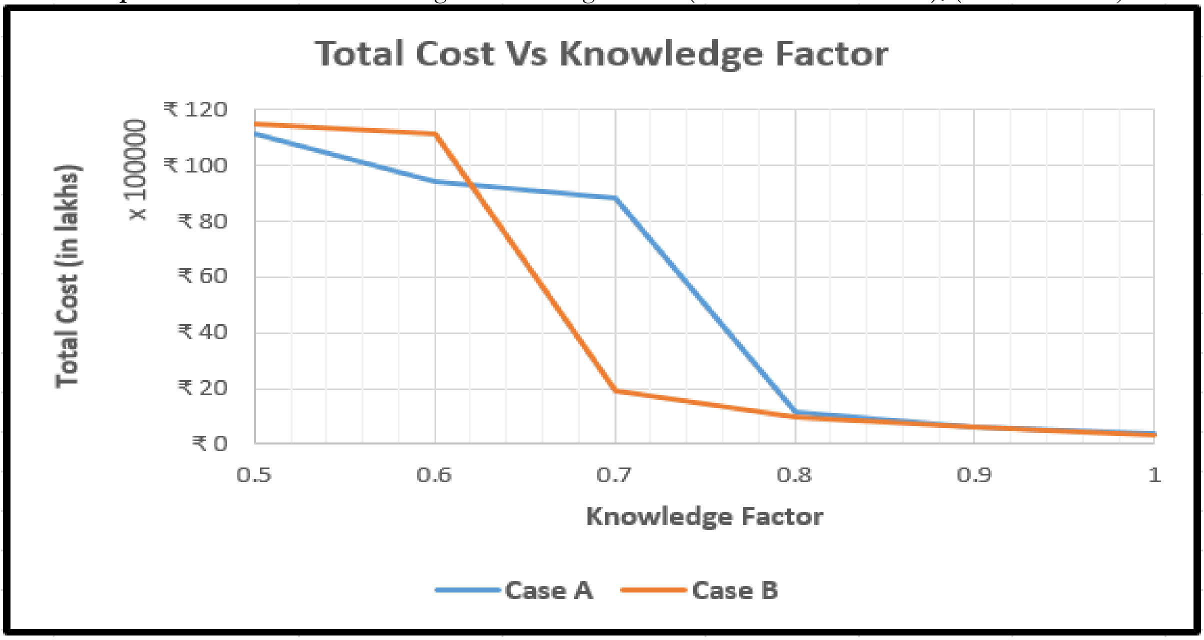
Case study A	**Items of work (Cost in Rupees)**			
Knowledge factor	**Concreting**	**Shuttering/ formwork**	**Reinforcement**	**Strengthening at member level**
0.5	62,63,775	13,48,470	9,06,390	25,87,003
0.6	62,63,775	13,48,470	9,06,390	9,23,930
0.7	62,63,775	13,48,470	9,06,390	2,95,658
0.8	0	0	0	11,57,992
0.9	0	0	0	6,40,591
1	0	0	0	3,69,572

Table 8: Cost of Items of Work for Addition of Shear Wall (Case B), (Source: Author)

Case study B	**Items of work (Cost in Rupees)**			
Knowledge factor	**Concreting**	**Shuttering/ formwork**	**Reinforcement**	**Strengthening at member level**
0.5	54,08,235	37,04,253	17,34,660	6,15,953
0.6	54,08,235	37,04,253	17,34,660	3,07,977
0.7	0	0	0	19,09,455
0.8	0	0	0	9,85,525
0.9	0	0	0	6,28,272
1	0	0	0	3,44,934

The graph 8, below represents the variation between the total costs of seismic retrofitting with the knowledge factor. The case studies were analysed after addition of shear walls wherever shear walls can be added to the structural system and there was reduction in the number of failed members. The addition of member decreases the internal forces on the structural members without increasing the capacity of the existing members. The reduction in structure displacement was also observed as compared to plan without shear walls. The cost analysis is conducted for the same and it was observed for the higher the knowledge level, there will be less or no requirement of shear wall system. The retrofitting/ strengthening can be performed at member level either through micro-concreting, or suing reinforced fibre wrapping or may be through jacketing.

Graph 8: Total Cost of Retrofitting Vs Knowledge Factor (Addition of Shear Wall), (Source: Author)



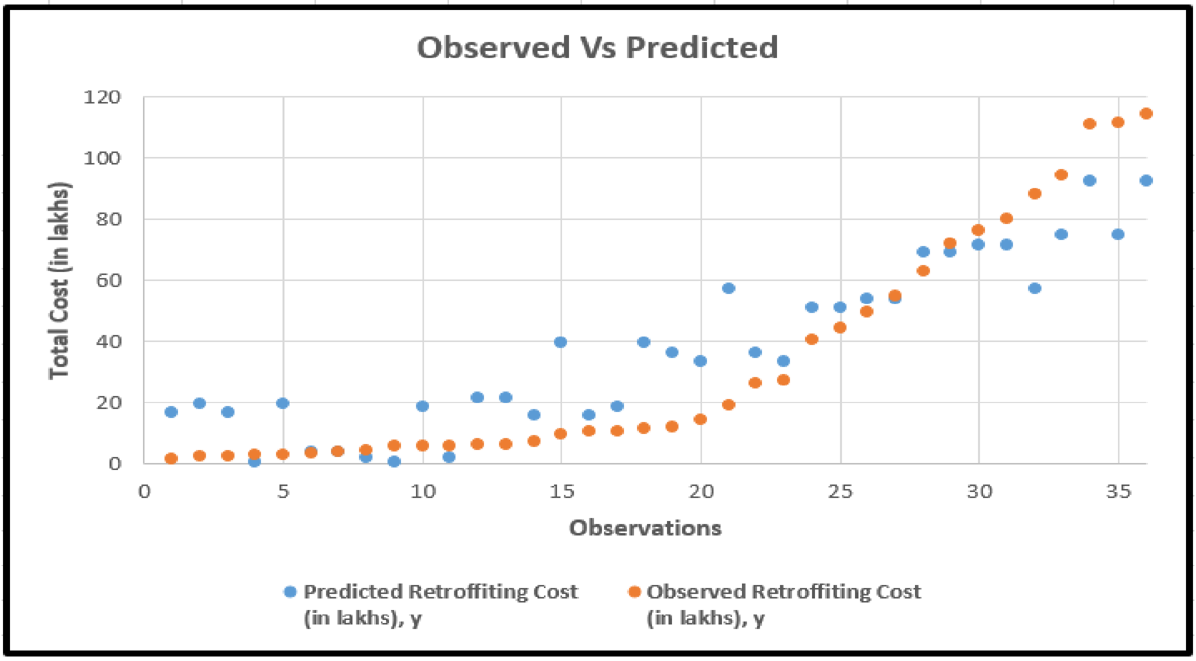
From the above graph, it can be observed that there is an increase in the structural retrofitting cost as knowledge factor decreases. The effect of knowledge factor increases rapidly when the amount of available information drops down significantly at the time of retrofitting.

The structural retrofitting cost due to knowledge factor 'k' and choice of retrofitting technique 'r' can be computed using the following linear relationship. Using the below equation, the predicted structural retrofitting cost and observed structural retrofitting cost are compared and represented in the graph below.

Y = 1.96*r1 – 2.76r2 + 20.90r3 + 177.386*k + 160.47

where,
y is the retrofitting cost in lakhs
k is the knowledge factor (unit less)
r1,r2,r3 are the dummy variables for the choice of retrofitting technique (either micro-concreting/ fibre wrapping/ addition of shear wall)

Graph 9: Observed & Predicted Retrofitting Cost (in lakhs), (Source: Author)



Conclusion

The research discusses the current state of the documentation management practices in the construction industry. The major causes of poor documentation found were lack of knowledge and willingness amongst the stakeholders and lack of software and trained personnel. The challenge at the time of retrofitting is the availability of documentation (architectural and structural drawings, foundation details, design calculations, geotechnical reports, material properties and records of at least natural period etc.) which hinders the knowledge factor. The change in the knowledge factor also cause the change in the seismic behaviour of the building. The analysis in the research was divided into two parts; first the seismic analysis of the building at different knowledge factor as defined by the IS Code and second was the cost comparison based on the different knowledge factor. According to the findings, when the knowledge factor is reduced from 1 to 0.5, the number of structural members that fail increases. When the knowledge factor is increased from 0.5 to 1, there was an average decrease in the structural retrofitting cost. The decrease in the cost can be achieved if the amount of information such as general drawings, detail drawings, technical reports, testing reports etc. are well documented and preserved at every stage of construction or post construction.

Future scope

This research has certain limitation which paves the way for further research in the area. To derive the concrete results sample size should be increased as only 2 case studies were considered in this study. The case studies were limited to high rise residential typology. The cost relationship is developed with three parameters (i.e. knowledge factor and choice of retrofitting technique) whereas other parameters like seismic zone factor, plan area, number of storeys in a building, building typology etc. could also be considered in the future.

However, the trend of the results refers only to the case study buildings and further investigations are needed in order to extend these results as general rule for the retrofit design of existing RC buildings. The impact in other seismic zones and for different building typology can also be researched further.

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