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Curbing the menace of reinforced concrete buildings collapse: A conceptual design and re-design approach for reversing the ugly trends

Timothy Oyewole ALAO[1,a*], James OLAYEMI[2,b] and Aliyu ABDUL[1,c]

[1] Department of Building, Federal University of Technology, Minna. Nigeria

[2]Department of Civil Engineering, Federal University of Technology, Minna. Nigeria

[a]timothy.alao@futminna.edu.ng, [b]olayemi.james@futminna.edu.ng, [c]aliyuabdul79@yahoo.com

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Abstract. Building collapse not arising primarily from the use of poor-quality materials has always been a worrisome concern to both Builders and Structural Engineers. This occurs, despite strict adherence to the fundamentals of structural mechanics employed in structural analysis and design. Case studies of total building collapse and avoidance of near collapse were discussed in the context of providing explanations for causes of collapse and measures employed to avert collapse of reinforced concrete buildings. Measures such as moment re-distribution, re-directing load paths, enhancing greater flexural rigidity, eliminating design flaws and construction sequence/methodology were discussed. Designing such a safe and efficient structural form using this conceptual design and re-design approaches would inherently satisfy both ultimate and serviceability requirements thus avoiding a total or near collapse of reinforced concrete buildings.

Introduction

Building collapse phenomenon

The commonly reported building collapse scenarios have always been attributed to poor quality materials usage on building construction projects [1,2,3]. However, building collapse can also arise from accidents caused by construction plants and equipment, which are often rare reported occurrence and, in such scenarios, sanctions, liabilities and remediations have been meted [4]. In all of these cases, a one-time visual inspection can reveal the causes and blames can be allotted to the regulatory agencies, consulting/supervising teams and the construction team. In contrast, building collapse that has been a worrisome concern particularly to construction professionals, are those scenarios where unexplainable causes are inherent at first sight. Such scenarios defy adherence to basic fundamentals of structural mechanics commonly employed in structural analysis and design [5,6].

Procedures for structural analysis and design

The procedure is guided in the form of design codes of practice and are spelt out in various code of practices which varied within countries such as BS 8110-Part-I and BS EN 1992 [7,8], which are improvements over the Code of Practice CP 114 and CP 110 encompassing the new design philosophy of the limit state principles. This process is guided by basic fundamentals of structural mechanics of materials. Several structural theoretical methods are employed such as the moment distribution method, the flexibility matrix method, the stiffness matrix method, the slope deflection and the clapeyrons (three-moments) methods for studying the nature, type and magnitude of internal stresses including deformation characteristics which reveals and empowers the designers for producing designs that are efficient and safe [9]. It is also practicable to develop mathematical derivations that mimics natures' mechanics to solve a number of structural design concepts. In this

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manner, innovative structural design concepts can be modelled and built. An example of this approach is the adaptation of the Fibonacci sequence which provides inspiration to optimal structural efficiency as demonstrated in the design of the Chinese World Trade Centre [10]. This structural concept mimics the bamboo's unique structural characteristics. It was demonstrated in this concept that the Bamboos diaphragm elements over the entire height are predictable mathematically [10]. The inspiration was curled from the ingenious nature and response of bamboos especially when subjected to Tsunamis to resist lateral forces.

Improving the strength of structural elements using new materials and technological process. Enhancing the performance of structural elements can be achieved using new materials. The use of modifying agents or additives can enhance strength and durability [11]. Erstwhile, a popular practice has been methods ranging from the use of composite materials with a view to increasing the flexural rigidity of the structural member, increasing percentage of reinforcing steels, increasing the overall dimension and use of prestressed concrete. A good example of increasing the flexural rigidity is in the use of reinforced concrete beam encasing structural steel I-sections which are often limited because of the overall cost implications [11]. Today, concrete is available in the form of self-compacting or self-consolidating concrete (SCC) including the use of super plasticizers and other chemical additives which can enhance greatly, workability, the compressive tensile and flexural strengths with reduced shrinkage [6,9,11,12]. This process enables concrete structures that can now be designed to prescribed level of load bearing and durability. Concrete produced which can now be measured in terms of strength, workability, compatibility, dimensional stability and resilience are now referred to as high-performance concrete (HPC).

Notably, the compressive strength of concrete has erstwhile increased from the highest of 55N/mm^2 up to 105N/mm^2 between a threshold of 20 years [11] due to these new developments. Because of earlier limitations on the achievable compressive strength levels till the end of 60's, concrete framed building with the highest number of floors, Pirelli Building in Italy was 127m high. There was a further innovation in the subsequent years. However, in the 90's, the Telekom Malaysian Towers was 310m high and now, the Burj Khalifa Building in Dubai, the United Arab Emirates is 800m tall. This is attributable to the increase in the static efficiency of concrete which can be depicted by Equation (1). The relationship between the compressive strength and unit weight of concrete is now as much as 4.7 times with an accompanying reduced cost which is marginally 3.0 times [11].

$$h_{sc} = \frac{f_c}{P_c} \tag{1}$$

Where h_{sc} is defined as static efficiency of concrete, f_c is the compressive strength of concrete and P_c is unit weight of concrete.

Improving the strength of structural elements using conceptual design approach
Architectural conceptual design process is also conceivable which are capable of enhancing performance of building fabrics and cost-in-use which can considerably enhance strength and reduce deterioration of structural elements and building fabrics [5]. A conceptual design process primarily refers to an intuitive and knowledge-based reasoning for allocating and maximizing space for functionality, aesthetics and efficiency of an architectural or structural layout. A structural conceptual design process permits an overall development of adequate resistance to strong wind loads, avoids undesirable stress distribution, thereby ensuring robustness of the building. It can also be explored in redirecting load paths aimed at overall optimal structural efficiency while avoiding concepts that creates maintenance concerns [5,6,12,13,14].

Focusing on the overall structural implications by synthesizing the structural system allows alternative structural layout to be evaluated from a multiple conflicting architectural design criterion. While this process can be more time consuming, the task of re-analyzing the structural frames can yield a more robust designs that are more efficient and also safe. However, numerous design Softwares which include SAP 2000, STAAD.Pro and Autodesk ROBOT Structural Analysis Professional are available to make this task seamless thus, reducing time consuming tasks of analyzing the structural frames.

The principle of a conceptual design approach should not be considered as a creative approach but as an intuitive reasoning process to create a structure that is not only functional but safe and in addition to this procedure should be at a reduced cost. Some practice procedures and Expert-based geometric modeling and parametric techniques have also been developed and employed to make decisions about the topology and geometry of the concept that is being created, with 3-D models for visualization and manipulation [13,14,15,16]. Authorities such as the United States Federal Highways Authority [15] has developed policies aimed at producing standard practices in the form of guidelines for ascertaining the overall implications of conceptual design solutions.

Balancing theoretical analysis and design

The process of balancing a theoretical analysis and design is aimed primarily, to satisfy the limit state principles of ultimate and serviceability satisfying both strength, deflection and stability [7,8]. This process is often dominated by the constraint of cost and thus, this limit offers designers to devise options that balances this constraint of cost. A balanced design requires an in-depth theoretical knowledge meeting both structural and constructability criteria by utilizing sound theories of structural mechanics and materials.

The use of commercialized/specialized application Softwares has made the task of theoretical structural analysis and design a less tedious and painful task and therefore, the designers are empowered to make judgements in a somewhat painless effort. In addition to computer packages that utilizes basic procedures of structural analysis and design, mathematical derivations that uses natures' mechanics can also be developed and used for structural analysis and also to ascertain the reliability of the design solutions [10,11]. These methods can also be an organically inspired solutions using genetic algorithms process that mimics the evolution of natural reproduction and selection. These methods are nonetheless possible but with the development of mathematical formulations describing the form often referred to as objective functions. The solution procedure is further simplified with the development of constraints formulations and boundary conditions in order to arrive at a feasible solution. This methodology, of course can lead to an array of solutions that the designer is able to make a choice of the 'best' solution.

Methodology

Load paths and re-directing load paths

Load paths can be described as the route within the structural frame along which the load 'flows' through [12]. Primarily, the loads from the roof and floors are transferred unto the beams, and then unto the columns which are then further transferred unto the foundation. Conversely, in a plane truss, the load path flows through the struts and ties unto the supports to foundations. Similarly, the foundation loads are transferred unto the earth. An analysis of the structural system reveals the type and distribution of stresses including the magnitude of displacements which could be horizontal, vertical, rotation or torsion in x, y or z axis. Identifying an efficient load path that minimizes the magnitude of these stresses would imply an efficient design which may not necessarily be a costlier option nor occupying more spaces.

These efficient ways of enhancing the carrying capacity of these members which may be either in flexure, tension, torsion or compression can be carried out through creative or an intuitive reasoning process. Many of the computerized analytical methods such as the global stiffness matrix method can make this task less cumbersome [9]. The design process ensures that all design criteria are met complying with both the ultimate, serviceability and stability requirements. Figures 1(a) and (b) shows an example of an idealized load path for the Pavilion, Raleigh, NC. A method

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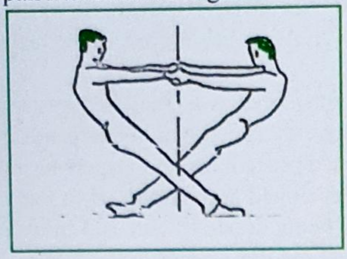
such as creating a continuous structural frame, over a number of supports reduces substantially, span moments through the increase of support moments.



(a) The mechanism

(b) The Bethlehem Steel structure

Figure 1: Pavilion, Raleigh Building, (Bethlehem Steel), NC: Courtesy of Fraser, (1981)

Moment re-distribution

In the elastic analysis of structural frames, concrete/reinforced concrete when compared to structural steel does not behave elastically near ultimate loads and for this reason, reinforced concrete frame can only be guaranteed for low stress levels [7,8]. In recognition of this, results of elastic analysis should further be evaluated in order to make the serviceability requirements to be within a tolerable threshold, possibly with values well below the specified limits. The code has recognized this phenomenon that, as the section nears the ultimate moment of resistance, plastic deformation occurs and a re-distribution of the estimated elastic moments can be employed to enhance the structural performance as depicted in Equations (2) and (3), [17]. By considering a span A – B for a uniformly loaded continuous beam, a support moment can be reduced by reducing an excessively large support moment value in Equation (2), and the corresponding shear force can therefore be re-calculated in Equation (3).

$$M_{BA_i} = \left(V_{AB_i} - \frac{w_i L_i}{2}\right) L_i + M_{AB_i} \qquad (2)$$

$$V_{AB_i} = \sqrt{(M_{max_i} - M_{AB_i})2w_i} \qquad (3)$$

$for\ all\ supports$ A_i and B_i; $maximum\ span\ moment$ M_{max_i}; $Current\ iteration\ of\ the\ shear\ force$ V_i; $span$ "L_i" $and\ udl$ "w_i"

The tolerable limit for this re-distribution is 30 percent representing a moment of resistance not greater than 70 percent at the cross section. The neutral axis depth is not to exceed the limit as described in Equation (4).

$$x \le (0.6 - \beta_{red})d \qquad (4)$$

As a precaution, for frames greater than 4-storeys, this moment reduction should not be greater than 10% particularly for frames in order to avoid lateral instability in the frame. The method is applicable to indeterminate structural frame. In this case, once a beam reaches its ultimate moment of resistance, any further stresses must be taken up partly by the adjacent part of the structure. This moment re-distribution is aimed at maintaining the static equilibrium of the structure. It is important to note that code provisions do not permit redistribution in column moments, [17].

Enhancing greater flexural rigidity

The process of elastic structural analysis and design start with member sizing. The magnitude of internal stresses is dependent among other factors on sizes, shape, form or orientation, length and type of materials used [17]. The flexural rigidity of a structural member can be enhanced by balancing the member properties. The expression in Equation (5) consists of three primary properties of the structure namely, The Young's modulus of elasticity "E" which is essentially a

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material property, the moment of inertia of the member "I" representing the cross-sectional or shape property and the overall length of the member.

$$Flexural\ rigidity = \frac{E_i I_i}{L_i} \quad (5)$$

$$for\ all\ member\ "i"$$

Secondary considerations such as end fixity, pre-strains and temperature conditions are also to be considered. However, designs that do not conform to mathematically proven solutions or lacking basic principles of structural mechanics are never acceptable. These procedures are basically to avoid structures that do not comply with codes to achieve prescribed safety levels. Engineered structures therefore must exhibit proven mechanics, construction technique, durability and sustainability [11,14, 17]. Where necessary, there may be a need to query a design output to satisfy some basic requirements in order to improve the design output to achieve a functional, stable and a durable structure.

Eliminating design flaws

The process of structural analysis and design are influenced by a number of factors including the use of alternative material or structural form. Change in material specification or use of composite material could sometimes be an un-economic option. In recognition of the requirement for a balanced design, option to change a structural form such as re-designing a section of the sub-frame and exploring an alternative structural layout should be explored.

However, collaborations between design teams to produce functional design solutions is encouraged so as to reduce conflict with architectural design concepts. Code requirements should not be a substitute for intuitive reasoning to produce efficient and safe structures [14,15]. Avoiding undesirable stress distributions and sway can ensure robustness of the building [5,6,10]. Walls are slender members [18] and therefore an exceptionally long and tall walls remains unstable including gable ends of roofs and must be designed to satisfy both strength and stability requirements. A code of practice therefore should not be a substitute for care and vigilance.

Construction sequence/methodology

The sequence of construction is an operational procedure and is well embedded in the practical knowledge acquired during training and practice. This process is usually well outlined and is a required contract document called construction programme representing a step-by-step activity known as tasks and sub-tasks. Nowadays, an evolving concept called Building Information Modelling (BIM), a digital visual representation of the construction process can also be used which allow a digital view and re-view of the overall process. During the construction phase, the structure can be acted upon by strong wind loads or lateral forces which may be foreseeable or unforeseeable. Adequate timing for removal or re-introduction of temporary supports to mitigate against collapse or lateral instability are desirable [6]

Discussion of Results

Scenario 1: Re-design and re-directing load path case study

The example shown in Figures 2(a) - (d) representing the plan and elevation of a storey building with the initial concept where there are four columns in a hall which will obviously obstruct view while the upper floor is to accommodate a residential use. The re-design involves removing the four interior columns resulting in a design output that violates all design criteria. The concept as shown in Figures 2(b) and (d) represents an iterative design output where all design criteria were satisfied. The process in Figure 3 shows the iterative history with the positioning of the columns showing different load path patterns. Column C_1 produced an un-satisfactory design with exceptionally large span positive moment. Column $C2_{L1}$ produced a design with the negative

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moment not reducing to zero showing that it exerts a negative moment on the foundation. However, in column $C2_{L2}$, the negative support moment has reduced to zero and the iteration was terminated because planning law/set back conditions with a combined footing introduced for columns C_1 and $C2_{L2}$.

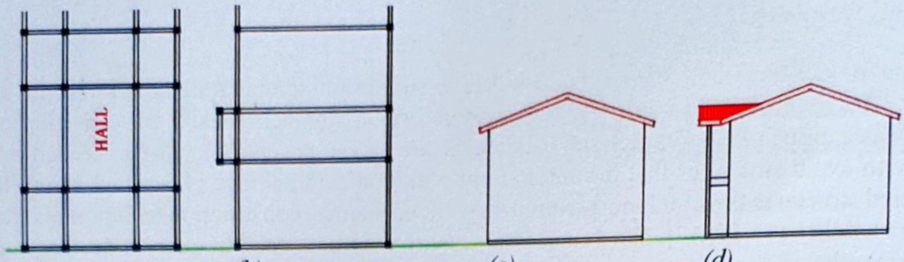

Figure 2: Re-design and re-directing load path example

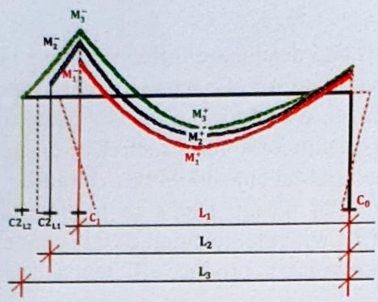

Figure 3: Iterative history of re-design example

The values of the span bending moment can be expressed as shown in Equation (6). Similarly, the maximum span moment can be estimated and occurs at the point where the value of the shear force is zero by equating the value of the expression in Equation (7) to zero. The effects of other loading systems can also be accounted for, in the equations.

$$M_{SPAN_i} = V_{SPAN_i}x - \frac{W{x_i}^2}{2} - M_{AB_i} \tag{6}$$

$$S_{SPAN_i} = V_{SPAN_i} - W_{x_i} \tag{7}$$

Scenario 2: Moment re-distribution example

The Figure 4 shown is a sub-frame example. The frame has five members, with six joints and three joint restraints are as shown. The design output showed a large negative moment at the interior support labelled $M_{\overline{R1}}^{-}$ while the span moment MR_1^+ was small. In accordance with the BS code, when design criteria cannot be met (such as percentage reinforcement, limiting deflection), the interior support moments can be reduced while increasing the span moments as described in Equations (2) and (3). However, the limiting percentage reduction is required not to exceed thirty percent. Where the storey height exceeds three, the limiting percentage reduction is not to exceed ten percent as shown in Equation (3). The iterative history is depicted as shown. In this manner, collapse can be averted using this iterative design procedure.

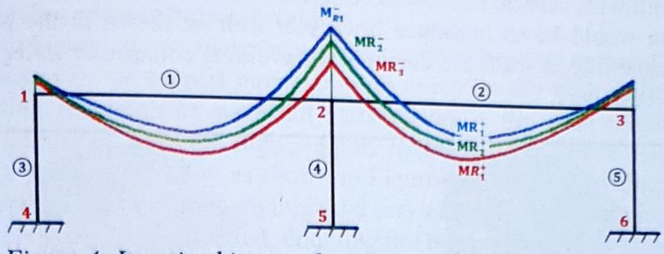

Figure 4: Iterative history of moment re-distribution example

Scenario 3: Eliminating design flaws

The scenario represents a collapsed building. Inspection showed a complete collapse without crushing of the beams. A sway of the entire building occurred, despite that the evaluated strength of the reinforced concrete beam showed a sufficient concrete compressive strength and sufficient number of tensile and compressive reinforcing bars. The plan of the initial frame is shown in Figure 5(a) while the re-built layout is shown in Figure 5(b). The mechanism of the collapse is shown in Figures 6(a) and (b).

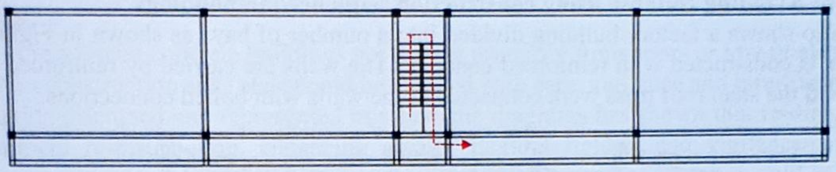

Figure 5(a): The plan of initial frame layout

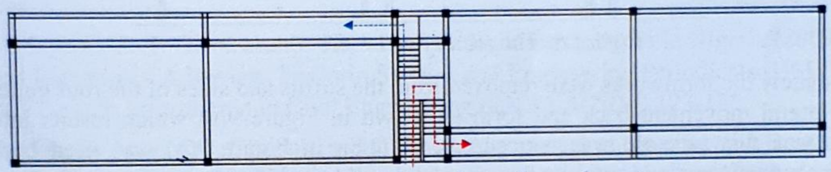

Figure 5(b): The plan of new frame layout

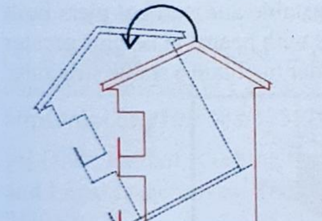

Figure 6(a): The idealized failure mechanism mechanism by sway

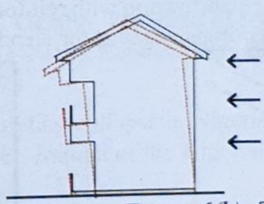

Figure 6(b): The idealized failure by tilting

Scenario 4: Avoiding collapse through ensuring lateral stability

In Figures 7(a) and (b), the point labelled as ①, the gable end collapsed by tilting inwards. This is in realization of the slenderness of the wall. This occurred in a hydraform laterite-cement interlocking brickwall. The collapsed brick did not break into fragments indicating that the brick strength is strong enough but lateral instability is responsible for the collapse. The Figure 7(b)

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shows a re-built wall with vertical reinforced concrete pier introduced at the beam level. Another alternative solution would be to introduce brick pier wall as shown in the point labelled ②. Avoiding lateral instability in walls are essential for avoiding collapse of walls, fences and gable ends of residential buildings.

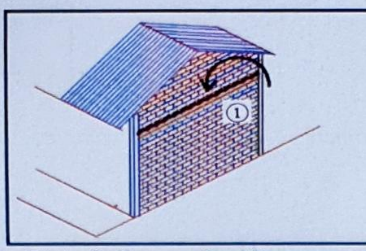

Figure 7(a): Collapse of gable end of vertical wall

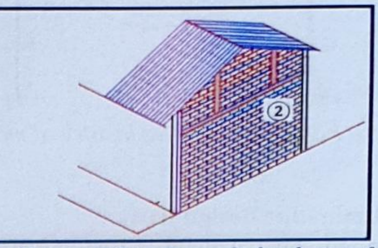

Figure 7(b): Remedial solution for the gable end

It is also worthy to note that the stability of walls can be enhanced by ensuring the structural members are tied to ensure a rigid frame. This can be achieved with the use of lintels and beams at window levels and at suitable heights to ensure walls do not collapse by lateral instability.

Scenario 5: Avoiding collapse using construction sequence/methodology

The scenario shows a factory building divided into a number of bays as shown in Figure 8. The roof gutter is constructed with reinforced concrete. The walls are carried by reinforced concrete columns and the steel roof truss were connected to the walls with bolted connections.

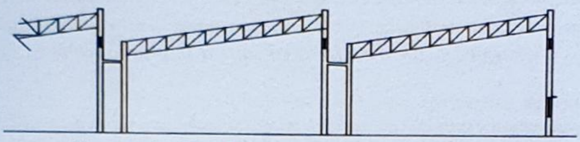

Figure 8: The factory cross-sectional view

Immediately the formworks were removed from the soffits and sides of the roof gutter, there was a lateral movement back and forth as shown in Figure 9(a) which results into a near collapse. Once this scenario was noticed, the solution in Figure 9(b) was used by building temporary sandcrete walls in between the column spaces to stabilize the roof gutter before the roof truss would be installed. In this manner, the roof gutter was stabilized. Similarly, tall walls, otherwise refered to as slender walls are vulnerable and remains unstable and vertical piers built of sandcrete blockwalls or stabilization with reinforced column piers with beams at heights greater than 2.0m are desirable to mitigate against the slender elements in order to obtain a stable structure.

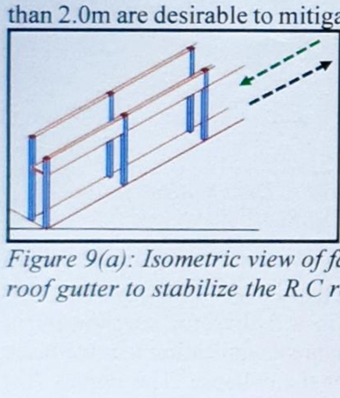

Figure 9(a): Isometric view of factory R.C roof gutter to stabilize the R.C roof gutter

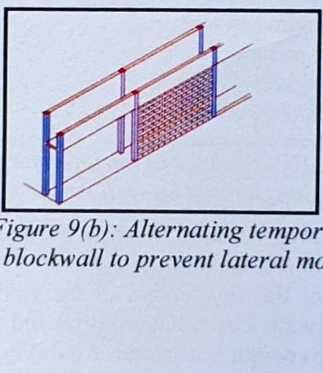

Figure 9(b): Alternating temporary sandcrete blockwall to prevent lateral movement

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Scenario 6: Enhancing greater flexural rigidity

The frame shown in Figure 10 was analyzed and the resulting bending moment diagram is shown in Figure 11(a). However, the support moments were exceptionally high and the design process showed that limiting requirements were not satisfied while the span moment was small in magnitude when compared with the high support moments. The frame's span moment was designed as a simply supported beam as shown in Figure 11(b), and providing sufficient tensile reinforcement to satisfy both the ultimate limit and serviceability states requirements. Where the architectural concept will not be impaired, doubling the beam in the point labelled ① in Figure 10 could also be an option in order to increase the flexural rigidity of the frame.

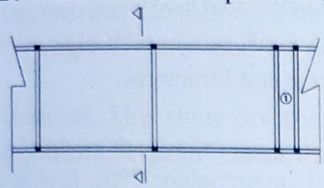

Figure 10: Plan of the frame

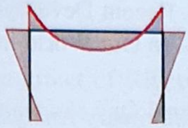

Figure 11(a): Initial bending moment

Figure 11(b): Bending moment of the re-designed frame

Conclusion

Collapse of reinforced concrete buildings not arising primarily from poor- or low-quality material can occur on construction sites and should be avoided with care, vigilance and intuitive reasoning. The scenarios discussed and represented in schematic diagrams has shown that re-directing load paths, moment re-distribution, enhancing greater flexural rigidity and vigilance/care during construction stage can reduce the ugly phenomenon. This process, obviously would enhance the creative thinking of Structural Engineers and Builders.

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