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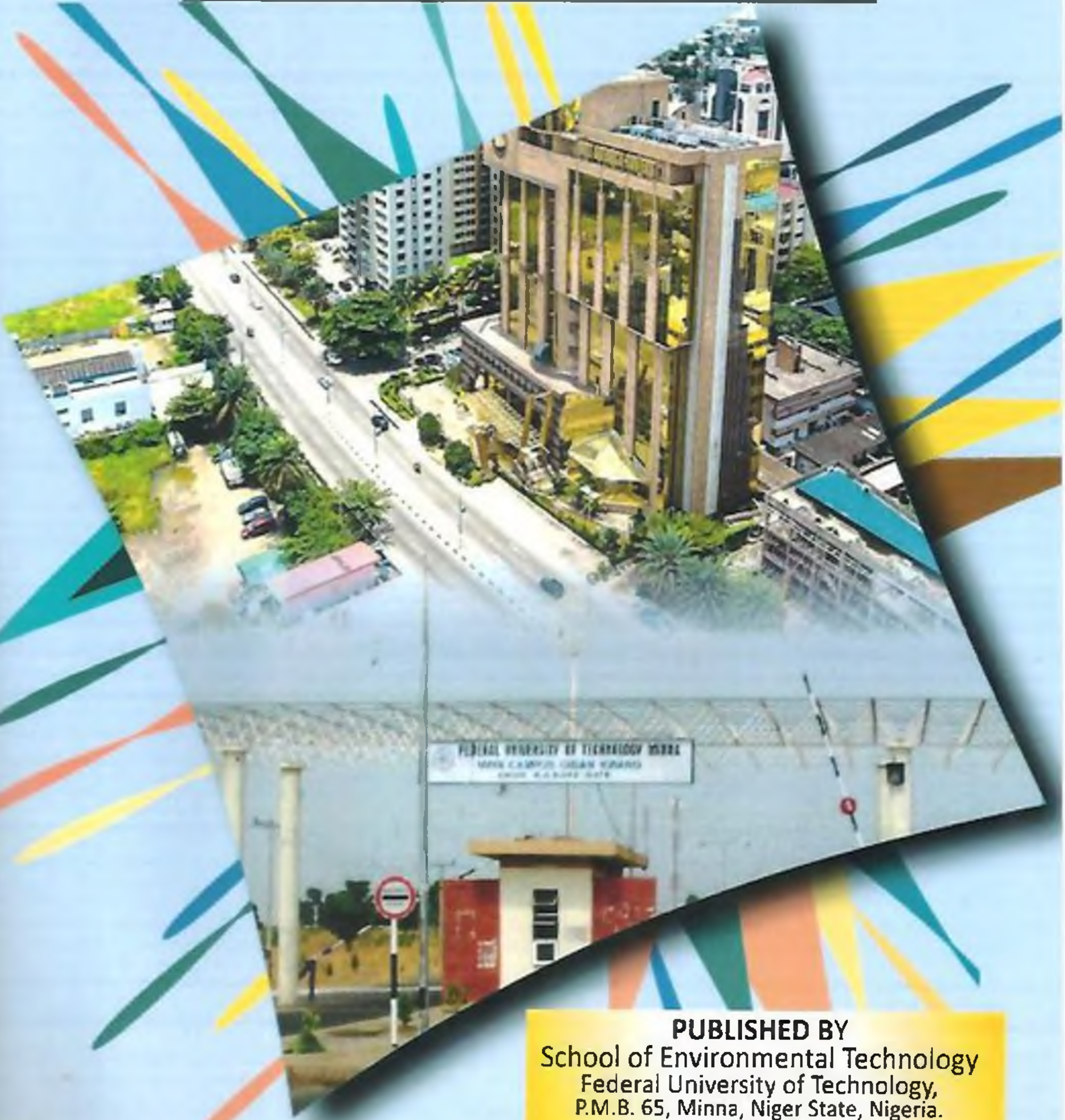

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Enhancement of the Efficiency of Building Systems through Conceptual Design

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Safe and efficient structural forms are practicable provided that the structural systems or forms can be described mathematically using mechanics in structural design. The concept of enhancing the efficiency of traditional buildings using a conceptual design approach is discussed with particular emphasis on redirecting load paths, moment redistribution and eliminating design flaws. The particular references to reinforced concrete buildings are discussed, to produce structures that are both functional and safe. Two examples of representative building frames were analysed to illustrate the working principles of this approach. It has been shown that conceptual design and re-design can improve the efficiency of designs and is therefore encouraged.

Keywords: Conceptual design, moment redistribution, load path, structural efficiency

Introduction

The procedures for structural analysis and design have been well developed including production of guidelines in the form of design codes. However, the challenges of analysis and design could present certain complex challenges. The decisions on the choice of a conceptual approach may not only be confined to a theoretical field of study alone but also including practical considerations too. The principle of a conceptual approach could be considered not only as an intuitive reasoning but also a creative act to produce a structure that is not only functional but safe and also at a reduced cost. Mathematical derivations can also be adapted using natures' mechanics in structural design concepts. This can lead to innovative structural design concepts. A good example is the adaptation of the Fibonacci sequence which provides clues to optimal structural efficiency as demonstrated in the design of Chinese World Trade Centre (Sarkisian, 2011), which mimics bamboo's unique structural characteristics. In this case, it was shown that Bamboos diaphragm elements over the entire height are mathematically predictable (Janssen, 1991). This material is particularly ingenious in its nature and response especially when subjected to Tsunamis to resist lateral forces.

A conceptual design process allows designers to synthesize structural systems by focusing on the overall structural implications of alternative structural layout while considering multiple conflicting architectural design criteria. This can then be followed by using numerous design softwares to aid in the more time consuming tasks of analyzing the structural frames. The principle of conceptual design would translate (Fraser, 1981; Hsu & Liu, 2000; Mola, Mola & Pellegrini, 2011; Alao & Ogunbode, 2019) to: Intuitive and knowledge based reasoning to allocate and maximize space for functionality, aesthetics and efficiency of a structural layout of a building frame. Thus

Permit development of adequate resistance to lateral forces in certain or foreseeable directions exposed to strong wind loads. Therefore, only code of practice should not be a reference material.

Avoid torsional effects and therefore avoiding undesirable stress distributions to ensure robustness of the building.

Redirecting load paths for optimal structural efficiency.

Today. Expert-based geometric modeling and parametric techniques have also been developed in order to make decisions about the most appropriate and efficient alternative structural layout concept (Fuyama *et al.*, 1997; Grierson & Khajehpour, 2002; Mora *et al.*, 2004; Kale, *et al.*, 2012). This enables visualization and manipulation of three-dimensional structural models. However, most of the available application softwares have been developed for bridge designs.

Similarly, development of policies, standard practices and guidelines for basic design steps aimed at ascertaining the overall structural implications of a conceptual design solutions have also been developed by authorities (FHWA, 2012). This paper focuses on the conceptual design of reinforced concrete framed buildings to assess the implications and advantages of alternative structural layout for enhancing efficiency of conceptual design solutions.

Theoretical Analysis and Design

In practice, theoretical analysis has to be balanced with design to satisfy the limit state principles of ultimate and serviceability for both strength and deflection respectively, (BS 8110: 1997; BS EN 1992: 2005). The constraint of cost often dominates the pre-requisite requirements for designers and hence, any structural forms or options are often restricted by same to produce final design specifications. However, modern designers are often grounded in theoretical knowledge to provide solutions meeting both structural and constructability criteria to produce a balanced design. The design of any structure therefore should consider the application of a deep knowledge in both theories of structural mechanics and material science. Today, the availability of application softwares has made theoretical solutions and analytical calculations much easier using modern day computers. Synergy should therefore exist between analysis and design and should therefore be pursued. Mathematical derivations that use natures' mechanics can be used in structural design (Mola, Mola & Pellegrini, 2011; Sarkisian, 2011). Similarly, the use of genetic principles which mimics the evolution of natural reproduction and selection can also be explored to obtain organically or nature inspired solutions. Once the mathematical equations can be developed and constraint formulations or boundary conditions are well defined, the structural form can be optimized to achieve the objective or cost function desired. Similarly, there may also be an array of solutions from which an optimal solution can be selected. Nowadays, there are a number of available softwares such as Matlab that can ease the solution procedure including specialized structural analysis and design softwares such as Structural Analysis and Design Program (STAAD Pro).

The Role of Designers and Code Development:

In the analysis and design of beams, the theory of beams in bending has been used to primarily derive the behavior of the beam elements. Consequently, codes guiding the design in bending and other behaviours have also been developed to achieve design goals. It is necessary to balance the theoretical knowledge and all analytical approaches to satisfy design codes and thus enhancing creative capabilities.

Modern society would however, not accept designs that do not conform to mathematically proven solutions or designs lacking basic principles of structural mechanics. This basically is to avoid structures that do not comply with codes which may inherently not meet some safety levels. It therefore implies that creativity must embed a theoretical knowledge and principles. More precisely, engineered structures must exhibit proven mechanics, construction technique, durability and sustainability (Mosley & Bungey, 1991; Hsu & Liu, 2000; Mola, Mola & Pellegrini, 2011).

The process of structural analysis and design start with member sizing, determination of internal stresses and selection of proportions of appropriate materials to produce a final design, (Mosley

& Bungey, 1991). Subsequent checks to meet certain ultimate and serviceability requirements are carried out. However, intuitive reasoning and thorough understanding of basic underlying mechanics of materials principles could improve the efficiency of the structural form. There is also a need to query a design output to satisfy some basic requirements to improve the design output in order to obtain a functional, stable and a durable structure.

Concrete Materials and Technology

Concrete elements have erstwhile been designed based on load carrying capacity considerations. However, concrete structures can now be designed to prescribed levels of both load bearing and durability. Similarly, the interaction between concrete as a material and reinforcing steels has evolved. Concrete performance can now be measured in terms of strength, workability, compatibility, dimensional stability and resilience or more precisely, an evolution of a high performance concrete. Concrete compressive strength has increased from highest of 55N/mm^2 up to 105N/mm^2 between a threshold of 20 years (Mola *et al.*, 2011) which has hitherto been achieved largely due to quality control. Before this time, it could only be achievable only with the use of structural steel. Before the end of 60's, concrete framed building with the highest number of floors, Pirelli Building in Italy was 127m high. In the 90's, the Telekom Malaysian Towers was 310m high and now, the Burj Khalifa Building in Dubai is 800m tall. This is because of the increase in the static efficiency of concrete depicted by equation (1). This essentially, is the relationship between the compressive strength and unit weight of concrete which can be as much as 4.7 times while the cost can marginally be 3.0 times

$$h_0 = \frac{f_c}{P_c} \qquad (1)$$

Concretes are also available as a Self-Compacting Concrete (SCC) with high workability; Reduced Shrinkage Concrete which are essentially in the form of fibre reinforced concrete (FRC), (Ogunbode *et al.*, 2017).

Code and code provisions for design of structural elements

Codes in the form of design codes have evolved over the years which are often articulated from theoretical and materials performance which are available for various materials usage. Conceptual design should therefore be judged based on both innovations/aesthetics with sound theoretical backgrounds to be able to conceive a structural form and investigate their behavior.

Unlike steel, concrete does not behave elastically near ultimate loads and therefore an elastic behavior can only be guaranteed for only low stress levels (BS 8110, 1997; BS EN 1992, 2005). Similarly, as the section approaches the ultimate moments of resistance, plastic deformation will occur. This recognition therefore allows redistribution of the elastic moments using equations 2 and 3, (Mosley & Bungey, 1991).

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

$$M_{BA_i} = \left(V_{AB_i} - \frac{w_i l_i}{2}\right) L_i + M_{AB_i} \qquad (3)$$

for all supports A_i *and* B_i, *span* i *and udl* "w_i"

It is based on the premise that the exact composite behavior of the member would depend on the relative quantities of the individual steel and concrete materials. However, it can be considered that a cross section that is virtually elastic until the steel yields and plastic when the concrete completely fails in compression. This process is however applicable to an indeterminate structure. Once a beam develops its ultimate moment of resistance, then a plastic hinge develops thus resisting a constant moment. For this reason, any further stresses must be taken up partly by the adjacent part of the structure provided it will not cause crushing of the concrete.

From a design point of view, some support moments are reduced and increasing some span moments in order to maintain static equilibrium of the structure, the percentage reduction is a measure of the rotation required at a hinge forming at that section. In accordance with BS 8110 and BS EN 1992, elastic moment reduction using moment redistribution is not to exceed 30% to avoid crushing of concrete at plastic hinges. For higher floors, a limit of 10% is imposed for floors exceeding 4-storeys so that lateral instability can be avoided in the framed structure. However, redistribution in column moments is not permitted, BS 8110: 1997.

The objective of the limit state design is to achieve an acceptable probability that a structure does not become unfit for its intended use. Neither should there be overturning or buckling in any critical section. This is invariably done by dividing both material strengths and loads by factors of safety.
Analysis of moments can be obtained by a simplified method using sub-frames or using a rigorous elastic analysis, (Weaver & Gere, 1980). Basic conditions laid down to be satisfied include (BS 8110: 1997):
i) Equilibrium between internal and external forces must be maintained
ii) Ultimate moment of resistance not greater than 70% of the moment of the cross section
iii) Moment reduction must not be greater than 30%
iv) For ultimate moment of resistance as a result of the redistribution, Neutral axis depth

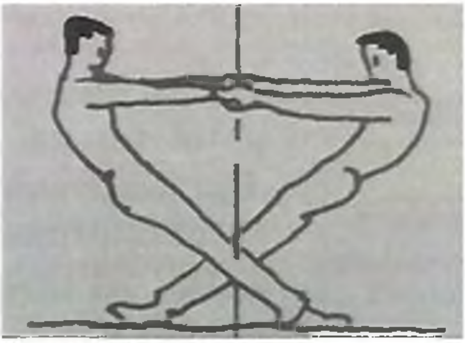
$$x \leq (0.6 - \beta_{red})d \qquad (4)$$

v) For frames providing lateral instability greater than 4-storeys, the reduction should not be greater than 10%

Load Paths

The route within the structure or a framed structure along which load 'flows' through, to the foundation could be referred to as a load path, (Fraser, 1981). As in the case of a plane frame, the load path travels through the beams, columns on to the foundation. Similarly, in case of a plane truss, the load paths travel through the struts, ties whose actions can be either compressive or tensile and transferred unto the supports to the foundation. A foundation could also be the solid earth, water as in the case of a floating crane or another part of a structure.
Structural analysis would reveal the distribution of stresses/displacements which could be horizontal translation, rotation or torsion in either x, y or z axes. Enhancing the structural efficiency of a structural system would therefore imply; identifying the structural system that can provide potential load paths. The resulting solution should not necessarily be costlier or occupying more space. The new structural form/solution could further be analyzed or probably optimized using appropriate fundamental mathematical tools for structural design. The attributes to achieve this are both inherent in the basic skill requirement and also intuitive reasoning.

In the selection of a structural form and loading a structural member, the type of forces the members are transmitting can be known through structural analysis and subsequently the load path arising from the arrangement (Weaver & Gere, 1980). It is imperative sometimes that certain acceptance criteria could not be met such as a maximum load carrying capacity, limiting deflection and torsion, conceptual design approach could be explored by re-distributing load paths to make it practicable. This method would rather obtain a solution at same reasonable cost than resorting to a choice of another structural material or utilizing another structural form. The solution therefore is to identify same structural form using the same material to provide load path that will serve the same purpose. An example of a load path for the Pavilion, Raleigh, NC is shown in Figures 1(a) and (b).



(a) The mechanism

(b) The Bethlehem Steel structure

Figure 1: Pavilion, Raleigh Building, (Bethlehem Steel), NC: Courtesy of Fraser, (1980)

The reinforced concrete sub-frame analysis

An analysis of two sub-frames using an elastic analysis of Stiffness method of structural analysis (Weaver and Gere, 1980) with the member and joint information are as shown in Figures 2(a) – (f) and 3(a) - (e). The beam dimensions are: overall height 450mm, thickness of slab 150mm and beam web thickness is 225mm. The young's modulus of elasticity for the two reinforced concrete frames are constant at 25KN/m^2 and 20KN/m^2 for Figures (2) and (3) respectively.

Figure 2(e) represents the initial design with interior columns and the desire to eliminate them in order to provide a clear view. The preliminary analysis of the plane frame with a uniformly distributed load of 60KN/m is shown in figure 2(f) and are presented in Tables 1(a) - (b) which shows that serviceability requirements were not met since the actual deflection of 90mm is far higher than the limiting deflection, L/360 representing 27.7mm.

Table 1(a): Actions as end of restrained members due to loads and member actions: Figure 2(f)

```
JOINT DISPLACEMENTS
JOINT  DJ1             DJ2         DJ3
1      3.316086E-02    -.9159112   -20.89479
2      -3.316442E-02   -.9159111    20.89479
3      0          0        0
4      0          0        0

MEMBER END-ACTIONS
MEMBER  AM1          AM2          AM3         AM4          AM5          AM6
1          51.61102  300          123.8938    -51.61102    300          -123.8937
2         322        -51.61102    -61.9059    -322          51.61102    -123.8938
3         322         51.61102     61.9059    -322         -51.61102     123.8938
```

Table 1(b): Actions at the supports and initial design span moments: Figure 2(f)

```
-------------------------------------------------------------------------------------------
S/No.   SPAN ID   SPAN L   SHEAR FORCE   SUPPORT   PT. OF ZERO   Mmax.    ACTUAL
                  (m)      (KN)          MOMENT    SHEAR                  deflection
                                         (KNm)     (m)           (KNm)    (mm)
-------------------------------------------------------------------------------------------

 1      1-2       10       300           123.99    5.000         626.106  90
-------------------------------------------------------------------------------------------
```

A modification of the frame with two parallel frames spaced at three (3) metres apart now carries a uniformly distributed load of 30KN/m over the entire span as shown in Figure 2(a) was an iterative process to relocate the interior columns by progressively adjusting the span until an optimal solution is met. Figures 2(b) and (c) represent the bending moment and the shear force diagrams respectively while figure 2(d) represents the member and joint information.

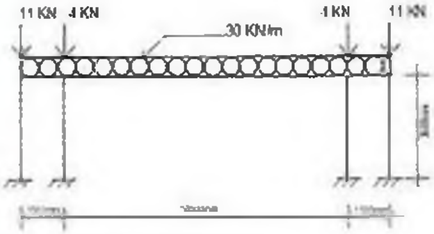


Figure 2(a): Loaded plane frame

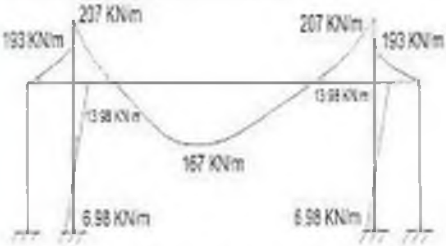


Figure 2(b): The bending moment diagram

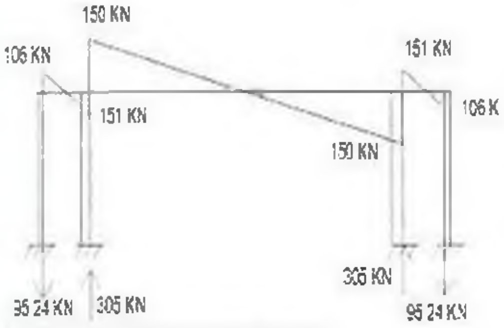


Figure 2(c): The shear force diagram

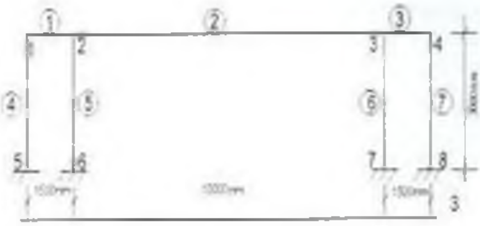


Figure 2(d): The member and joint information

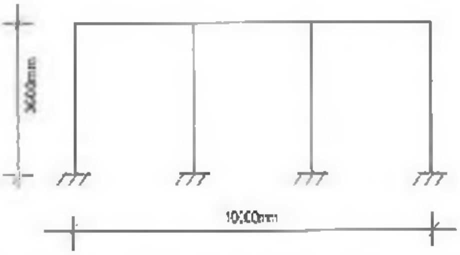


Figure 2(e): The initial concept with interior columns

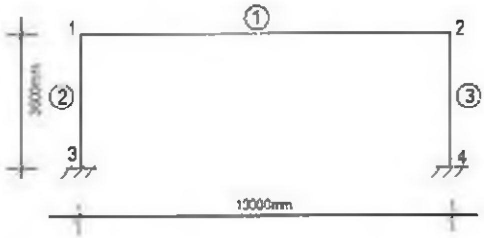
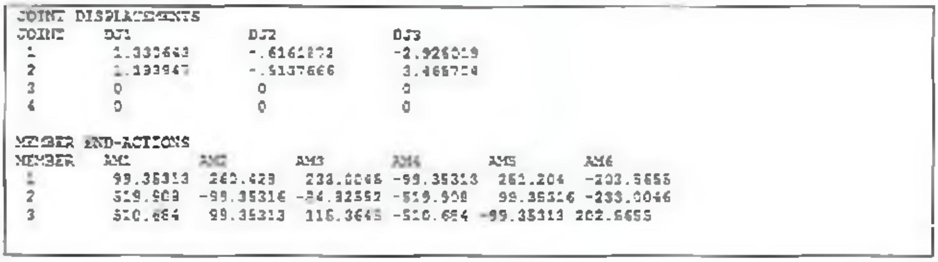


Figure 2(f): The member and joint information for the preliminary analysis

Figure 3(a) represents the interior of the sub-frame for example 2. The preliminary analysis in Table 1(c) shows that the support moment is excessively high representing 233KNm and the expression in Equation (5) is violated having the left hand side expression with a value of 0.305 which is greater than 0.156.

$$\frac{M}{bd^2 f_{cu}} \leq 0.156 \qquad (5)$$

Table 1(c): Actions at end of restrained members due to loads and member end actions: Figure 3(b)



```
JOINT DISPLACEMENTS
JOINT     DJ1             DJ2             DJ3
 1         1.333643       -.6161272       -2.926019
 2         1.193947       -.5137666        3.466724
 3         0               0               0
 4         0               0               0

MEMBER END-ACTIONS
MEMBER    AM1         AM2         AM3         AM4         AM5         AM6
 1         99.35313   262.428    233.0046   -99.35313   262.204    -202.5655
 2         519.909   -99.35316  -84.32552  -519.908     99.35316  -233.0046
 3         510.654    99.35313   115.3645  -510.654   -99.35313   202.5655
```

A modification of the design is not feasible and limiting cost would not permit the use of alternative material or structural form. The beam was designed as a simply supported beam and all serviceability requirements were met. Figures 3(b) and (c) represent the initial bending moment and the shear force diagrams respectively while figure 3(d) represents the member and joint information.

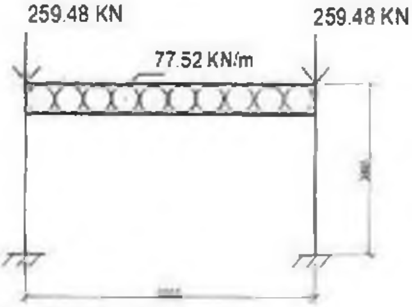


Figure 3(a): Loaded plane frame

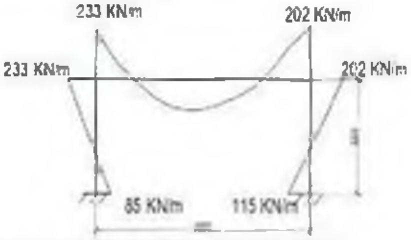


Figure 3(b): The bending moment diagram

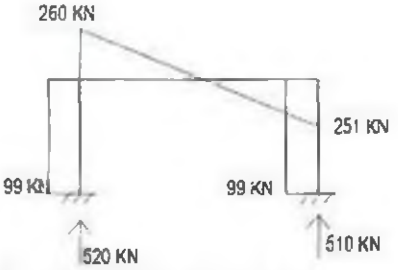


Figure 3(c): The shear force diagram

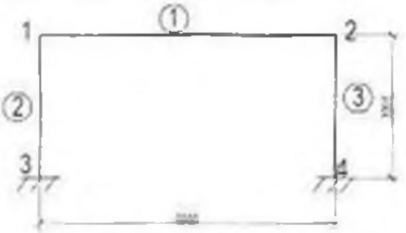


Figure 3(d): The member and joint information

Figure 3(e): The alternative Bending Moment Diagram

Analysis and discussion of results

The resulting rotation corresponding to the bending moment in Figure 2(b) is still very large and there is the need to carry out a moment redistribution using equations (2) and (3). The resulting values after iteration yields a mid-span moment of 195KNm as against 167.93KNm yielding a moment reduction of 25.69% which is still below the threshold of the limits suggested by the code of practice BS 8110 and BS EN 1992. The Actions at the end of restrained members due to loads and the member end actions are as shown in Table 2(a). The values of the initial unknown actions are shown in Figure 2(b) and the iterative history for the moment redistribution is also shown in Table 2(c).

Similarly, the load path has changed as there is upper vertical translation at supports 5 and 8 in Figure 2(d), which necessitates a combined footing for the foundation.

Similarly, for example 2, a computer aided design would not have revealed the apparent design error. The load path has been properly redefined and serviceability requirements are now met.

The resulting maximum bending moment can now be calculated as in equation (6) as:

$$M_{max} = \frac{wl^2}{8} \qquad (6)$$

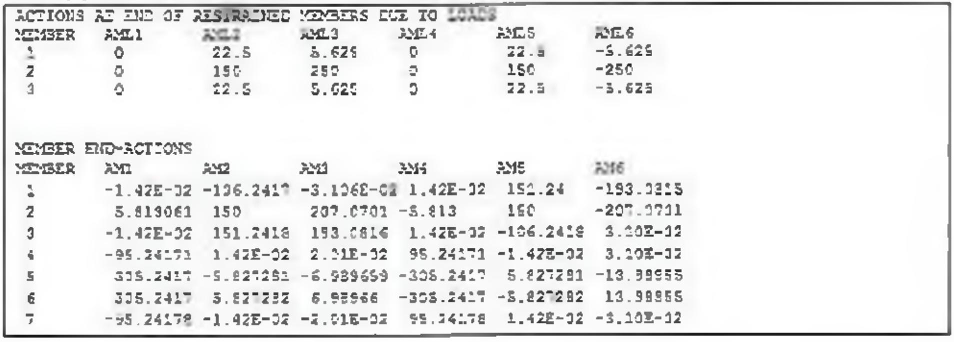
This represents a value of 422.1KNm

Benefits of the load path

This offers:

i) A reduction in center span moment
ii) Reduction of interior support and end-moments
iii) Change in the mechanism of redistributing the load by introducing a combined footing for transfer of axial loads and moments
iv) Provides a clear interior span with full vision within the hall
v) Prevented sway

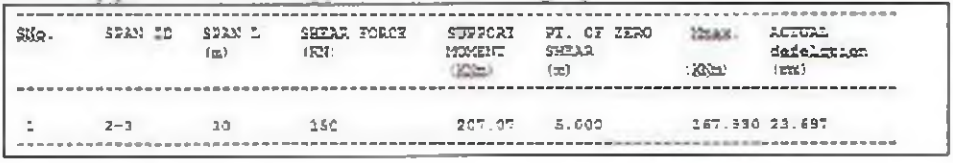
Table 2(a): Actions at end of restrained members due to loads and member actions



```
ACTIONS AT END OF RESTRAINED MEMBERS DUE TO LOADS
MEMBER   AML1       AML2       AML3       AML4       AML5       AML6
 1         0         22.5       5.625      0          22.5      -5.625
 2         0         150        250        0          150       -250
 3         0         22.5       5.625      0          22.5      -5.625


MEMBER END-ACTIONS
MEMBER   AM1        AM2        AM3        AM4        AM5        AM6
 1       -1.42E-02 -106.2417  -3.106E-02 1.42E-02   152.24    -193.0815
 2        5.813061  150        207.0701 -5.813      150       -207.0701
 3       -1.42E-02  151.2418   193.0816  1.42E-02 -106.2418   3.10E-12
 4       -95.24171  1.42E-02   2.31E-02  95.24171 -1.42E-02   3.10E-12
 5        305.2417 -5.827281  -6.989659 -305.2417  5.827281 -13.98955
 6        305.2417  5.827282   6.98966  -305.2417 -5.827282  13.98955
 7       -95.24178 -1.42E-02  -2.01E-02  95.24178  1.42E-02 -3.10E-12
```

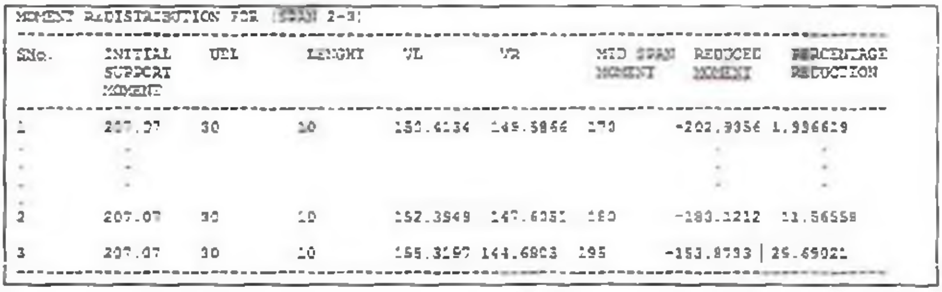
Table 2(b): Actions at the supports and initial design span moments



```
------------------------------------------------------------------------------------
SNo.    SPAN ID   SPAN L    SHEAR FORCE    SUPPORT   PT. OF ZERO    Mmax.   ACTUAL
                  (m)       (KN)           MOMENT    SHEAR                  defelction
                                           (KNm)     (m)            (KNm)   (mm)
------------------------------------------------------------------------------------

 1      2-3        10        150            207.07    5.000          267.330 23.697
------------------------------------------------------------------------------------
```

Table 2(c): Iterative history for moment redistribution



```
MOMENT REDISTRIBUTION FOR (SPAN 2-3)
------------------------------------------------------------------------------------------------
SNo.     INITIAL   UDL      LENGHT   VL        VR        MID SPAN  REDUCED    PERCENTAGE
         SUPPORT                                         MOMENT    MOMENT     REDUCTION
         MOMENT
------------------------------------------------------------------------------------------------
1        207.07    30       10       150.4134  149.5866  170       -202.9356 1.996629
.          .                                                          .          .
.          .                                                          .          .
.          .                                                          .          .
.
2        207.07    30       10       152.3949  147.6051  180       -183.1212  11.56558
3        207.07    30       10       155.3197 144.6803  195       -153.8733 | 25.69021
------------------------------------------------------------------------------------------------
```

Conclusion

As demonstrated in the plane frame examples, a safer and efficient structure can be achieved by employing rational solutions through conceptual design. In contrast to building collapse arising from poor building material usage, design errors arising from concept could similarly result in defective structures and therefore, adherence to code requirements should not be a substitute for intuitive reasoning to produce structures that are efficient and safe. A conceptual design through exploring alternative structural layouts should be explored. They are usually at no extra cost and can produce not only a safe but an efficient structure. Collaborations between design teams to produce functional design solutions is encouraged in order to avoid conflicting architectural design concepts. An Expert-based geometric modeling and parametric techniques should also be explored to aid this process for building structures.

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