VALUE-BASED DESIGN OF STEEL HIGH-RISE BUILDINGS

Karim M. El-Dash*

ABSTRACT

The presented paper discusses the design of steel high-rise buildings with respect to the main structural-related functions controlling the design configurations and their impact on the value of the building. The process of value engineering as standardized by SAVE International is utilized in the value analysis model proposed in the study. The study demonstrates the relationship between total quantity of material, connections, height of building, and construction methodology and the resultant cost. On the other hand, gravity load sustainability and experienced drift due to lateral loads are analyzed along with other main structural configurations of the building.

The paper demonstrates an illustrative example for the key relationships between the value and the considered parameters. The main model that is considered in the example is a 16.00 *m* x 30.00 *m* constant rectangular area with variable height from two floors to sixty-four floors. The structural system is a rigid frame system that is compared to the tubular system with columns spaced at two meters apart. The effect of wind direction and the availability and uncertainty of the database of wind loads on the design process is discussed in the presented study.

INTRODUCTION

If enhancing the attributes of a building in turn increases the value of that building, will the result be a better building? The answer to this question depends greatly on the perspective from which the building is evaluated, but in general terms the results should be better buildings since enhancing the attributes of the building and its value should lead to greater client satisfaction, provided that these goals are achieved without excessive cost. Financial modeling of a high-rise building is an important part of the design process of the project because this technique is the basis for key decisions, and result in an analytical understanding of the project and its requirements. So, it is needed to utilize quantitative techniques for evaluation of the feasibility of the different proposed alternatives for the project. Nevertheless, adequate testing of needs, functions, and objectives is crucial to determine the best value for money with respect to the considered task [Best–1999].

When attempting to evaluate the building it is needed to take account of the varying worth that different individuals will attach to the subjective factors related to value. These include intangibles such as spaciousness and utility [Westney-1997]. So, when market value is assessed, due allowance must be made for these factors as well as the more readily quantified component such as the cost of physical components of the buildings. The process of value engineering/ value management (VA/VM) accounts for the value from different perspectives with accord to the stakeholders of the project and their needs and tolerances [Shillito–1992]. The structural characteristics of a steel high-rise building are very complicated and dependable interchangeably [Taranath-1988]. The quantitative comparative analysis for these characteristics is an apt mean to find out the optimum decision to be made for the structural configuration of the building.

* Department of Civil Engineering, Faculty of Engineering at Shobra, Zagazig University.
k_eldash@hotmail.com

STEEL HIGH-RISE BUILDINGS

It is difficult to distinguish the characteristics of a building that categorize it as tall. From structural design point of view, it is simpler to consider a building as tall when the lateral loads in some way affect its structural analyses and design, particularly sway caused by such loads. As building heights increase, the natural forces begin to dominate the structural system and take on increasing importance in the overall building system. The Council on Tall Buildings and Urban Habitat (1995) defines the unique nature of the high-rise building as: "A building whose height creates different conditions in the design, construction, and use than those exist in common buildings of a certain region and period."

If there were no lateral loads such as wind or earthquake, any high-rise building could be designed primarily for gravity loads [Gupta – 1993]. Such a design that considers the gravity dead and live loads only would be the minimum possible material for a building of any number of stories. Assuming equal bay size, the material quantities required for gravity floor framing in low and high-rise structures are essentially identical. However, the material required for the vertical system, such as columns and walls, in a high-rise structure is substantially more than that for a low-rise building. The material increases in the ratio of $(n + 1)/2$, where, n, is the number of floors, because the vertical components carrying the gravity loads will need to be strengthened for the full height of the building, requiring more vertical materials than a one-story structure having the same floor area [Taranath-1988].

The quantity of materials required for resisting lateral loads is even more pronounced would exceed all other structural costs if rigid frame action were employed in very tall building. Wind begins to show its dominance at about 50 stories and become increasingly important with greater height. Above 50 stories, wind-bracing ingenuity often makes the difference between an economical solution and an expensive one [Ju – 1999]. The increase in material for gravity load with steel building is less than that with reinforced concrete buildings. On the other hand, the additional material required for lateral load is not much higher than that for concrete structures, since weight of additional gravity in concrete structures helps to resist the lateral deflection and overturning moment. The additional gravity load can aggravate the problem of designing for earthquake forces [Westney-1997].

VALUE ENGINEERING & VALUE MANAGEMENT

The process of value engineering depends primarily on the functions of the considered task and the evaluations of these tasks. The process needs the contribution of many disciplines involved in the task/project with their different perspectives to the evaluation of its constituents. The main phases of the value engineering process are described hereafter.

Origination Phase

In the origination phase, a value engineering study team is planned and the project, requirements, and restrictions are defined. The performance and cost targets are set and the team members are selected and trained for the value engineering process. Traditionally, the main criterion for identifying a value-engineering project has been high cost such as high-rise buildings.

After the project is identified, personnel need to be assigned to the study team. The team must contain a mix of people from areas that can contribute effectively to the mission. The success of a value study is enhanced when organizational and political aspects of the study are considered when selecting team members. Teams range in size from three to seven members and make extensive use of part-time assistance from other stakeholders in the project.

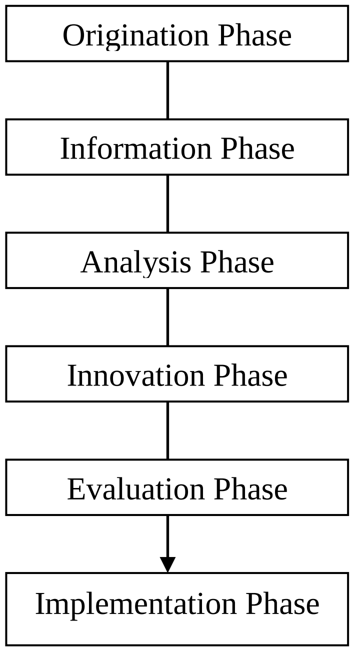

Figure (1): Phases of Value Engineering Process

Information Phase

In the information phase, the project and its utility are examined in detail to obtain a thorough understanding of its nature. The cost and performance of the structure is compared to other analogous structures. Constraints that dictate geometric configuration, material, construction methodology, serviceability tolerances, and budget are challenged for validity. This analysis produces a detailed breakdown of the structure that shows main components, their costs, and performance specifications and tolerances.

The value engineering team has to obtain detailed information about the components of the structure under consideration to answer, "*What is it*?" question. Each component is listed and categorized at an appropriate system level. After the full definition of the components, the cost of each component is determined. Cost consists of actual costs such as material and labor costs in addition to the overhead cost. Generally, in a high-rise structure, the main elements could be decomposed into flooring elements, gravity elements, and lateral load resistance system.

During this phase, it is important to get information on the desired performance of each component and for the structure as a whole. These data should include the spacing between columns, openings requirements, space utility, allowable deformation, relative column shortening, floor drifts, lateral deformation, soil bearing capacity, material properties, and any other specific data [Tsai-1989].

Analysis Phase

In the analysis phase, the functions of the structure and its components are documented by "*Function Analysis*" technique. Functions have importance and cost; these are quantified by "*Value Management*" techniques and an ordered list of function importance and value is created.

Function analysis answers the value question; "*What does it do*?" and is unique to value studies. The method requires that only two words, a noun and a verb, describe functions. After functions are identified, they are frequently classified as basic or secondary. The basic function is the prime reason for existence of the structure. Secondary functions support the basic function/s and allow them to occur. Although secondary functions may improve dependability or convenience, they are often prime candidates for elimination or improvement and innovation.

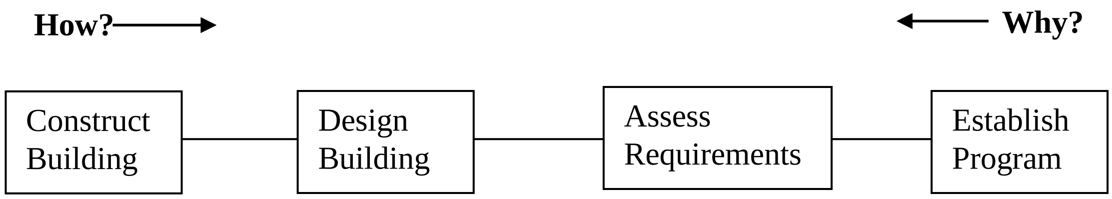

Figure (2): Basic FAST diagram for construction projects

Function Analysis System Technique (FAST) diagrams are used to classify functions. These diagrams order functions in a hierarchy based on how and why specific function is performed. They display the causal interrelationship of all functions. Value teams classify functions also using function spreadsheets. They consist of a matrix in which components are arrayed against the major functions present in a component. They are often used to determine function costs. Figure (2) shows a very concise model for a FAST diagram of a construction project. The actual diagram for a value study would include more details for the constituting functions and the interrelationships among them as per SAVE standards.

In value measurement, the question "*What does it worth*?" is answered. The value of components and its features are measured. The relative importance of components and functions is measured by comparison using a number of different subjective rating techniques. Numbers are used to weight the importance of components and functions, and the subjectively derived numbers are normalized to a percentage. The relative importance of an item in a system is calculated in terms of its contribution to the performance of the total system.

Innovation Phase

In the innovative phase, creative techniques are used to generate design alternatives. Many different alternatives are listed to improve performance and reduce cost before judging the merit of these alternatives. There are many techniques for generating and collecting ideas. Techniques can be classified along a continuum based on the degree of freedom and the structure used in the creative process. For high-rise buildings, the value team should has the capacity and the experience to innovate suitable alternatives that enhance the behavior of the structure and reduce the costs of the considered components. The prime component that is subject to modification is the lateral load resistance system that varies significantly with the configurations of the structure. There are possible structural solutions that are normally considered in the development of high-rise projects. The main options are briefed in the following:

* Cross-bracing system:
    a. Exterior braced tube.
    b. Interior braced tube.
    c. Braced and framed tube combination.
* Framed tube systems:
    a. Framed tube with 2.00-6.00 m column spacings.
    b. Twin tubes with 2.00-6.00 m column spacing.
* Nontubular system:
    a. Shear wall frame interaction.
    b. Moment frames and core braces.
    c. Outrigger and belt trusses.

Evaluation Phase

The evaluation phase categorizes ideas, gathers information about their feasibility and cost, screens the ideas, and then measures the value of the best ideas. The process repeats that used to analyze the current product in the information and analysis phases of the job plan. The initial analysis is referred to as a present state analysis; repetition of this analysis on ideas from the innovation phase is referred to as future state analysis. In prescreening exercise, the ideas are examined for redundancy, and any redundant ideas are eliminated. The ideas are then categorized into different design approaches and appraised against criteria constraints such as performance, cost, quality, and so on.

Implementation Phase

In the implementation phase, a report summarizing the value study is prepared. It contains conclusions and makes specific proposals. Action plans for implementing the recommendations are described. An oral presentation is an excellent supplement to a written document. A major factor in obtaining acceptance and use of recommendations involves making the decision maker feel comfortable with the recommended changes. Having the decision maker as a team member is ideal. Ownership increases the chances for acceptance and positive action.

FUNCTIONS

The determination of the main functional requirements is not an easy task. Ranking primary functions in order of importance is the normal approach. These functions are combined with detailed technical requirements that can suppress the process. Attention needs to be placed on the overall functional requirements of the structure; these will guide the functional use analyses of the detailed building components at a later stage. The primary functions in the case of high-rise structure are as follows:

1. Support loads; including framing, flooring, live loads, and self-weight of the structure.
2. Sustain wind; comprising the gust winds with its considered direction as well as all major wind loads from other directions that need to be considered in the design according to statistical history of the region.

3. Sustain earthquakes; involving the anticipated effect of the earthquake on the structure based on the regional distribution of the seismic zoning.
4. Provide shelter; which is the prime function of any building. Sheltering in all types of buildings is to supply the users by the needed haven to utilize the given space.
5. Ensure function; with respect to the utility of the building in its required detailed functions as stated by the architect. The deformability of the structure is the prime concern in the function definition, where the excessive deformations create a case of unease for the stakeholders of the building.

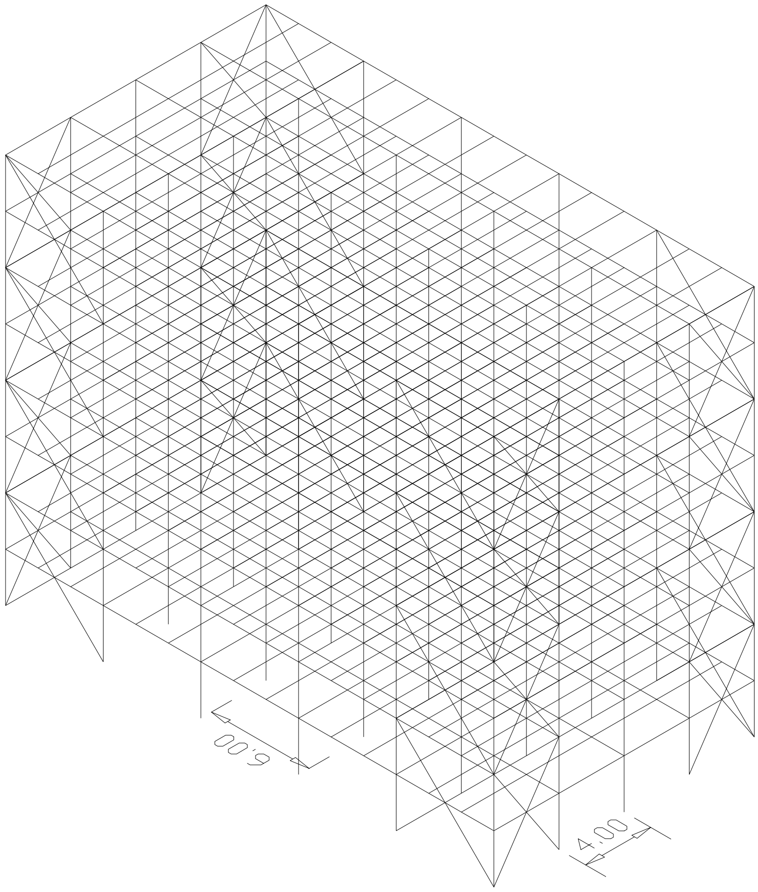

Figure (3): Lateral load resistance using rigid framing system

EXAMPLE - INFORMATION PHASE

A schematic model is exploited to illustrate the utilization of value engineering/ value management process for the structural design of steel high-rise buildings. The model as shown in Figure (3) is of 16.00 m X 30.00 m area divided into 5 bays in the long direction (X-direction) with 6.00 m span for each bay and 4 bays in the short direction (Y-direction) with 4.00 m span for each bay. The height of the stories is assumed to be 3.00 m without any change along the whole elevation of the building. The maximum height considered in the analysis is that of 64 floors that add up to 192 m height. The study considered variable heights of the building to sense the effect of the utility added by increasing the floors with respect to the increase in the cost of the building considering the excess cost of the unit area of the structure.

The design of high-rise structures faces the challenge of resisting lateral loads. The first system that considered in the study was utilizing rigid 3-D frame with exterior bracing at the corners of the structure as illustrated partially in Figure (3). This type of bracing is similar to that designed and presented by Qi (1999). Figure (4) shows the second alternative that depends on utilizing excess columns at the perimeter of the structure to comprise a core system that enhance the behavior of the shell on the outside of the structure and reduce the interchanging stress in the interior framing elements of the structure. The third model presented depends on the existence of truss bracing system at the perimeter of the building at each other floor of the complete elevation of the building. Figure (5) shows the distribution of the truss bracing elements on partial height of the structure.

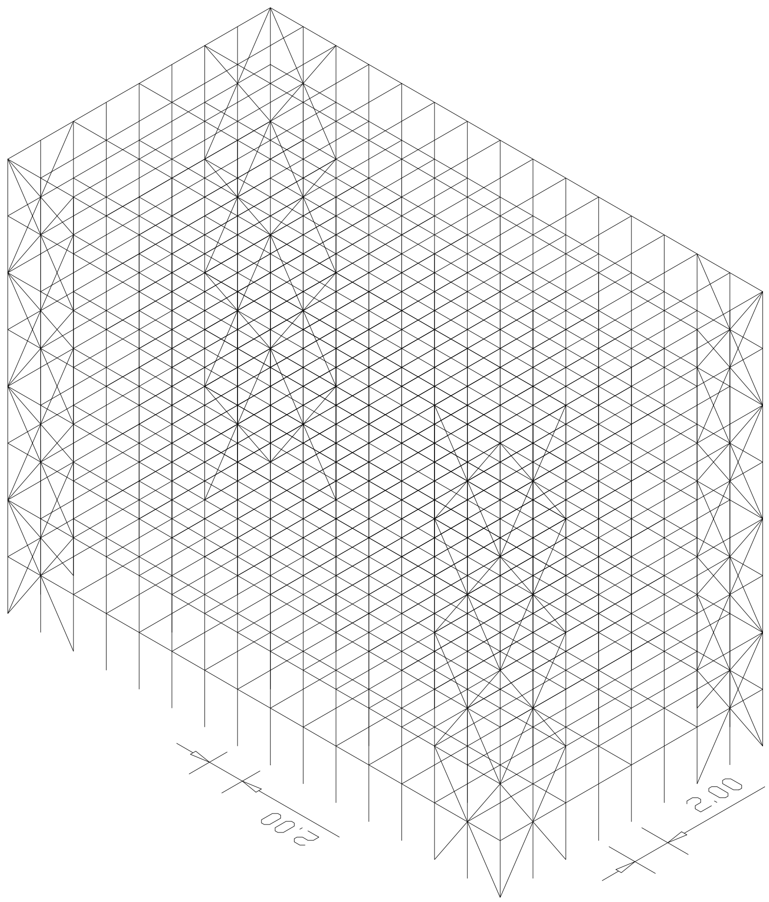

Figure (4): Lateral load resistance using tube system

Design Attributes

In the design process, there are many attributes that contribute to the criteria of the design, the processes approach, and the decision made for the final design. The prime parameter in the design of high-rise building is the height of the structure. Despite that the decision of the height is the architecture's decision in the low-rise building up to 20-30 floors, he is not the sole decider in the case of high-rise buildings when the structural system and cost become focused upon in the decision of the height. The soil capacity, foundation system, superstructure configuration, lateral load resistance, and physical performance of the structure are major features for the height decision.

The sensitivity of the height with respect to the required material and the cost of steel per unit area was analyzed. Two main lateral load resistance systems were considered in the sensitivity analysis; the rigid frame system and the core system. Both systems were changing from 6 m to 192 m height. Also, the corresponding lateral drifts for each case of the considered two sets of models were analyzed. The lateral loads assumed to be constant over the complete height of the building for all models. It is common for the design of high-rise buildings to use information for gust speeds over the history of 100 years. The value of wind loads is assumed equal to 100 kg/m^2 while the seismic load is neglected in the analysis assuming that the considered wind load would compensate for the effect of earthquake. The load direction is considered for all four directions based on the high uncertainty of data in many cases in the developing countries [Zhou-2000].

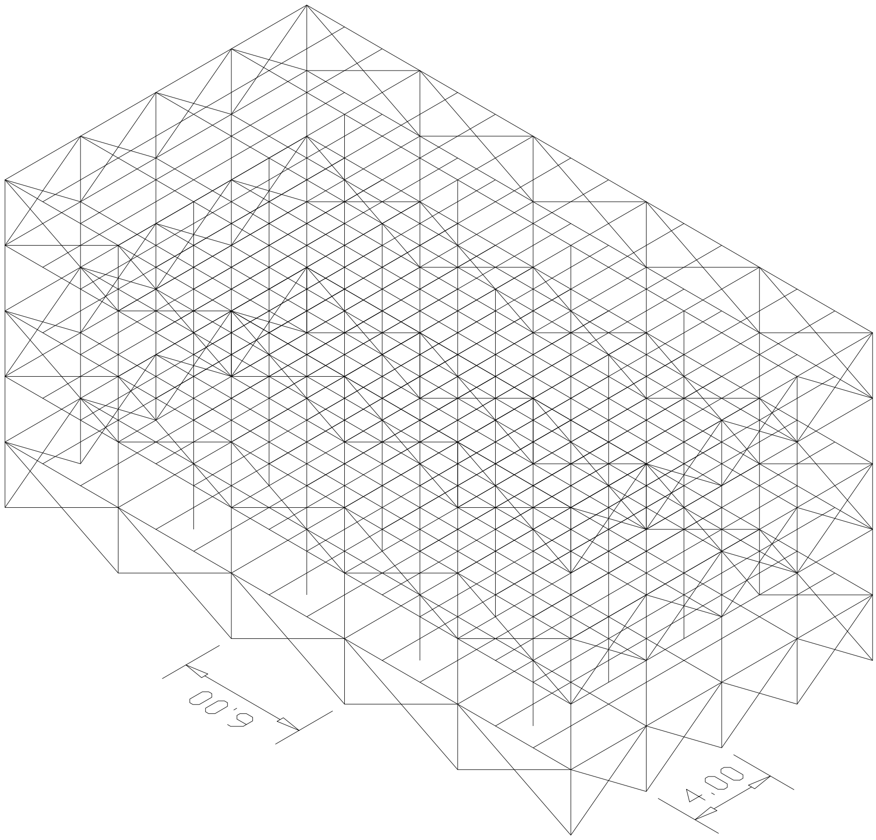

Figure (5): Lateral load resistance using exterior truss system

The spacing of columns plays a major role in the behavior of the high buildings. When the columns are close to each other, the building behavior is drastically changing. The large spacing makes the columns behave individually, while small spacing integrates the behavior of the structure considerably that the load distribution over the columns redistributed according to the lateral load, height of structure, aspect ratio of the plan view of the building, rigidity of the framing connections, spacing of columns, and stiffness of spandrels. The column spacing effect on the behavior of the high structures is represented in the study through the comparison between the results obtained from the rigid frame system and the core system. In the core system, the spacing between the columns on the perimeter was reduced to 2.00 m on all four sides of the building, while the interior module of columns kept as 4.00 m and 6.00 m for the short and long directions, respectively.

EXAMPLE - ANALYSIS PHASE

The cost distribution for medium-rise steel structures is divided among material, labor, and erection. Low-rise buildings demand less cost for the erection and connections than that required for material, while for the high-rise structures, the erection portion of cost gets higher depending on the height of the structure and easiness of erection with respect to the interior and exterior spaces as well as the structure configurations. The quantity of structural steel as

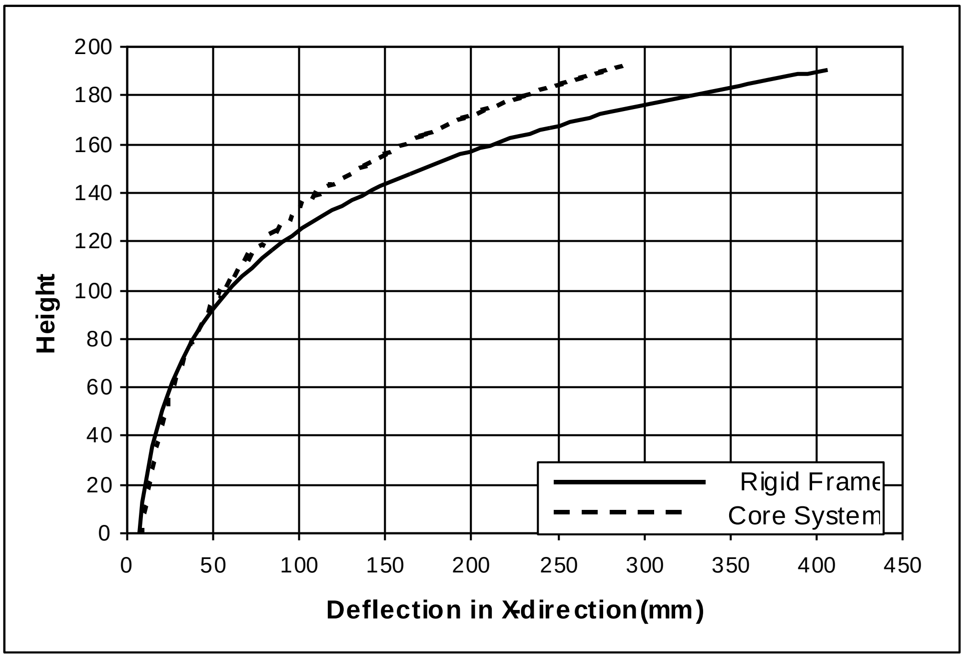

Figure (6): Relationship between height and deflection in X-direction

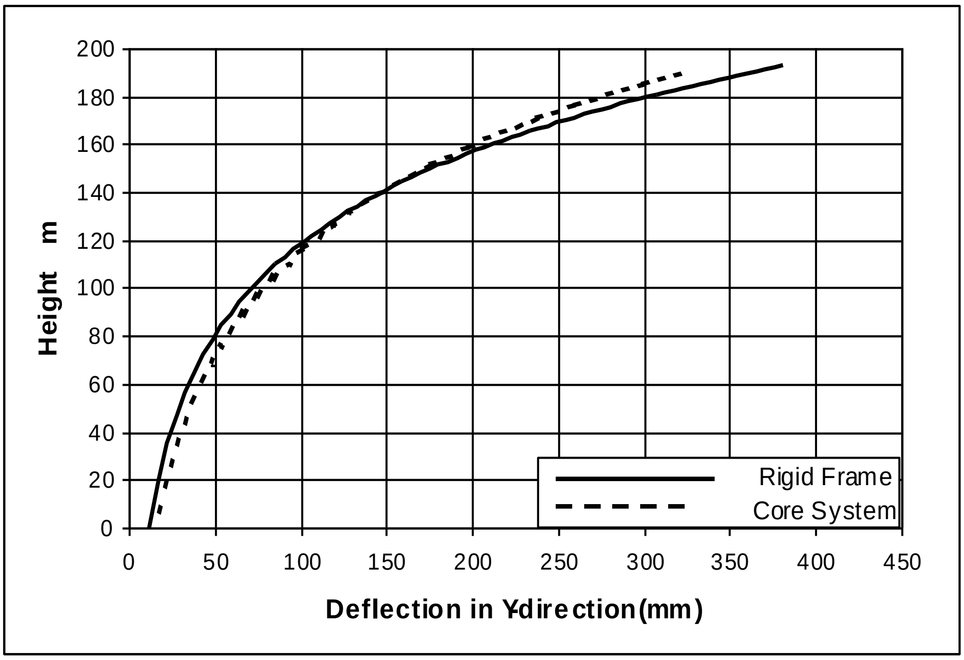

Figure (7): Relationship between height and deflection in Y-direction per the analyzed models is assumed to have a linear proportional relationship with respect to the total cost of the structural body.

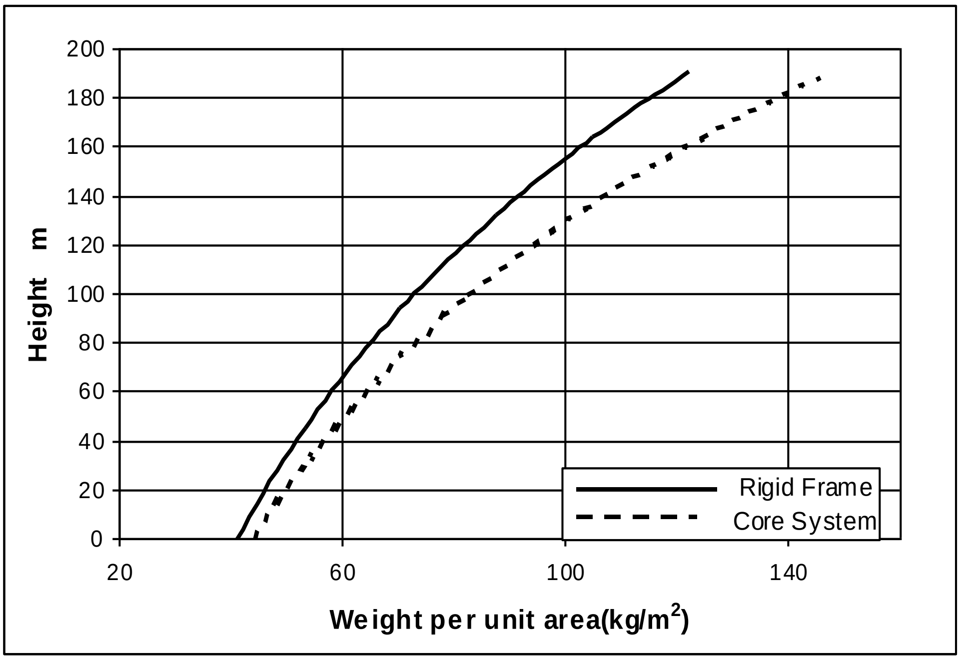

Figure (8): Relationship between height and material weight per unit area

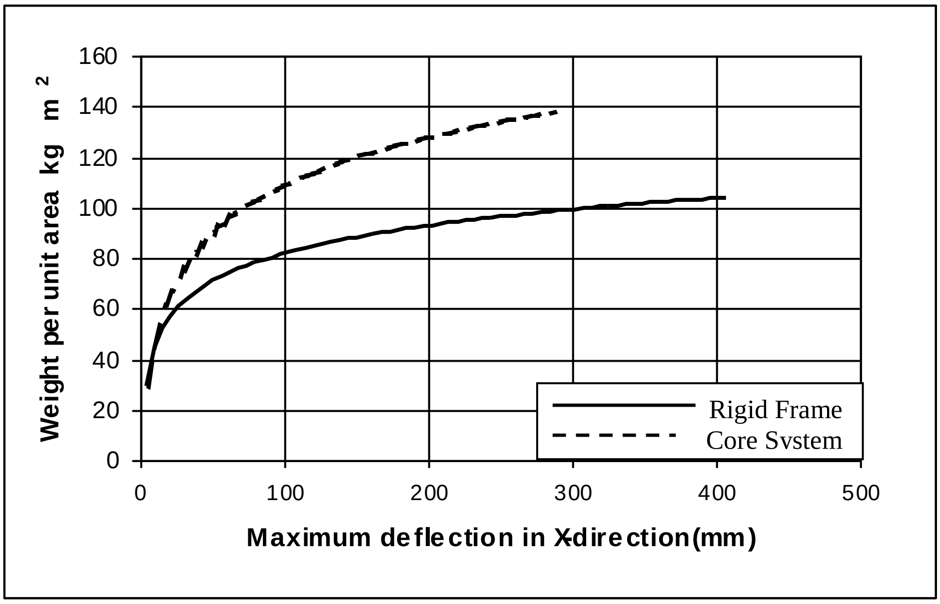

Figure (9): Relationship between material used and deflection in X-direction

The analyses conducted on the different models, as described ahead, show the effect of the height of the structure on the increase of the total drift of the structure. The software of SAP2000 was utilized in the analysis and design of sections for the varies configurations considered for the presented models. Figures (6) and (7) show the relationship between the drifts in the X-direction (short direction) and Y-direction (long direction) measured in (*mm*) and the total height of the structure. The effect of the core system on the drift of the structure is effective starting from 60 m height and increasing dramatically for larger heights. On the other hand, the effect of using the core system shows lower enhancement for the drift in the long direction, where the stiffness of the structure is higher with respect to lateral loads in the same direction.

The relationship between the weight of material (structural steel elements) per unit area, measured in *kg./cm*^{2}, and the total height of the structure, measured in *meters*, is shown in Figure (8). The weight of structural steel for the core system has only 2% excess over that for the rigid frame system when the height of the structure is only 6.00 *m*. This difference increases with the increase of the height of the structure as seen in the figure up to about 20% when the height of the structure is 192.00 *m*. These relationships are combined together in Figures (9) and (10) to elaborate the relationships between the drifts in X-direction and Y-direction and the corresponding weight of the structural steel per unit area. The figures show that the effect of using core system increases the cost as represented by the weight of material and reduces the total drift of the structure in both directions remarkably. It is to be noted that the increase in the cost here depends on the more sensitive direction regardless of the rigidity of the structure in each direction.

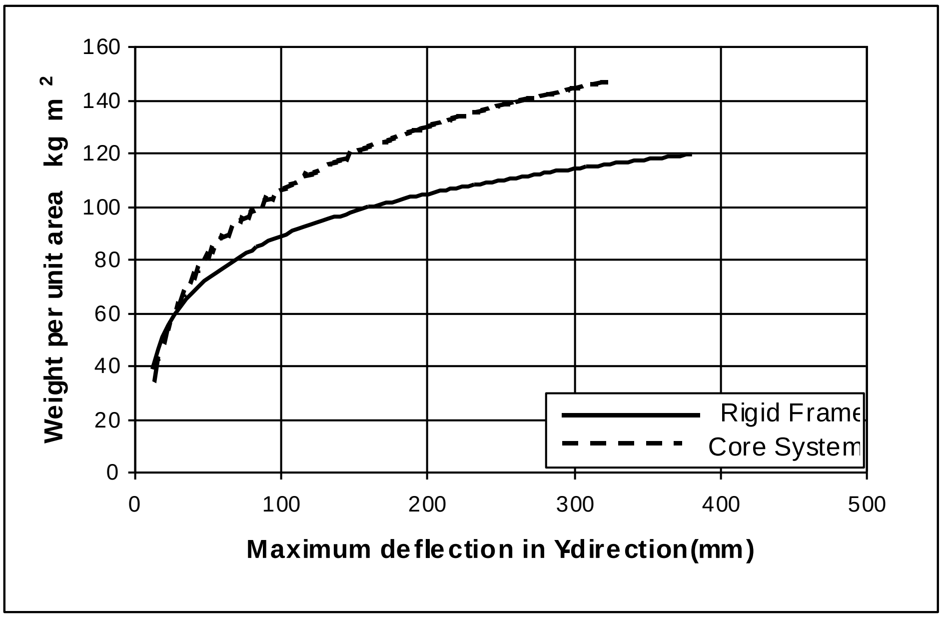

Figure (10): Relationship between steel weight and deflection in Y-direction

The main systems considered for lateral load resistance were compared to another system that depends on the truss bracing elements at the perimeter of the structure. The comparison included the height of 192.00 *m* only. The behavior of the later system shows better performance especially for the deformation in the short direction that reduced by about 22% while there is almost no change in neither the deformation in the long direction nor in the total weight of the material to be used with this system. This results show enhancement in the value of the structure since the performance would be increased while the cost should be without any increase. The details of the process for the evaluation phase is long and dependent on the value team participating in the process. Hence, it was intended only to present the main guidelines for the application of the value engineering methodology in the field of the design of steel high-rise buildings.

CONCLUSIONS

The following conclusions are brought about from the previous analyses and related discussions:

– VA/VM methodology is an advantageous mean to make a decision for the optimum structural system for a steel high-rise building. It considers the tangible and intangible attributes of the structure and their added value to the stakeholders as well as the cost for these items.

– VA/VM is required that the value team has the knowledge and skills to collect and handle the information required for the analysis and recommendation processes. The knowledge areas should include the structural engineering, architectural requirement, owner needs and tolerances, investments policies, and all other specific conditions.

– The steel high-rise buildings are very sensitive to the configuration of the utilized lateral resistance system. The optimum system depends on the geometric dimensions of the building, applied gravity and lateral loads, height of the building, allowed deformations, and the financial policy of the owner.

REFERENCES

ASTM Subcommittee E06.81 on Building Economics, (1994), "ASTM Standards on Building Economics", ASTM, Philadelphia, USA.

Best, R. and Valence, G., (1999), "Building in Value; Pre-design Issues", Arnold, Great Britain.

Council on Tall Buildings and Urban Habitat, (1995), "Structural System for Tall Buildings", McGraw Hill, Inc., International Edition, Singapore.

Gupta A. J. and Moss, P. J., (1993), "Guidelines for Design of Low-Rise Buildings Subjected to Lateral Forces", CRC Press, Inc., Boca Raton, USA.

Ju, S. H. and Lin, M. C., (1999), "Comparison of Building Analyses Assuming Rigid or Flexible Floors", Journal of Structural Engineering, Vol. 125, No. 1, pp. 25-31.

Qi, X., Chang, K. L., and Tsai, K. C., (1997), "Seismic Design of Eccentrically Braced Space Frame", Journal of Structural Engineering, Vol. 123, No. 8, pp. 977-985.

SAVE INTERNATIONAL, (1998), "Value Methodology Standards", SAVE Int., USA.

Shillito, M. L. and Marle, D., (1992), "Value; Its Measurement, Design, and Management", Wiley-Interscience, John Wiley & Sons, Inc., Canada.

Taranath, B. S., (1988), "Structural Analysis and Design of Tall Buildings", McGraw Hill Book Company, New York, USA.

Tsai, K. C. and Popov, E. P., (1989), "Seismic Panel Zone Design Effect on Elastic Story Drift in Steel Frames", Journal of Structural Engineering, Vol. 116, No. 12, pp. 3285-3301.

Westney, R. E., (1997), "The Engineer's Cost Handbook; Tools for Managing Project Costs", Marcel Dekker, Inc., New York, USA.

Zhou, Y, Kareem, A., and Gu, M., (2000), "Equivalent Static Buffeting Loads on Structures", Journal of Structural Engineering, Vol. 126, No. 8, pp. 989-992.