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Full Length Research Paper

Assessment of industrial and adaptable building components for a residential layout

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From environmental point of view, building waste is a critical issue in present construction. In order to reduce the depletion of valuable materials and natural resources, waste management of constructions needs to be considered in the early stages of design. This requires innovative design strategies that take into account the future demolition and provide flexible and versatile structures. Industrial, flexible and demountable building system (IFD) is trying to create buildings with higher quality, more adaptable and better environmental characteristics. But till date, a recognized method for IFD building assessment has not been defined. This research focuses on IFD component analysis process for a residential terrace house layout. In the first step of the research, a conceptual prototype for the key elements was proposed. Next step was to create a procedure for evaluating the suggested design. The evaluation process contains two parts. First, the layout and design characteristics assessment according to IFD criteria was developed. Second, the stability, seismic and load bearing capacity of the designed structure was characterized by conventional nonlinear static analysis (pushover) through finite element computations with ETABS software. It is proposed that, application of these assessments can testify to the flexibility and strength of the designed layout.

Key words: Industrial, flexible and demountable building system (IFD), building components, modular coordination system, terrace house layout.

INTRODUCTION

Construction could be defined as transformation of materials, resources or components into buildings and infrastructural works (Egmond and Scheublin, 2005). In fact, a building construction process is a complex system that involves required interactions between different parties. On the other hand, in most of developing countries, insufficient cooperation between the parties have caused dysfunctional team works, and lots of opportunities for optimal use of resources as well as innovations in design and construction. Yet, conventional ways of construction ignores the in-built capacity of the building for easy adaptation over time (Paduart et al., 2008; Razaz, 2010). Therefore, any change or renovation of the building will not be easily possible or result in significant cost and waste during its lifecycle (Sunikka and Boon, 2003; Tam et al., 2006). Besides, customers' demands for variable production output, require the construction industry to make the process of production more flexible for achieving higher quality products with variety of kinds (Egmond and Scheublin, 2005). Industrial and flexible system tries to improve the way of building construction in such a way that result in a faster, economical, higher quality and environmental friendly building in comparison with traditional methods (Bon and Hutchinson, 2000; Ball, 2002; Kohler and Hassler, 2002; Zegers and Herwijnen, 2004; Gallant and Blickle, 2005).

However, flexible and reusable construction system can only be attained if the design process considers the general construction system and construction detailing at the same time (Paduart et al., 2008). Therefore, attention has to be paid to the integration and technical requirements of the elements and the connections as well. This research project focuses on analysis process of an IFD terrace house layout. The first step is to define the

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criteria for flexible and dismountable building elements. In order to objectively assess whether the design meets these set of criteria, an evaluation method was developed. The evaluation method helps to recognize where improvements can be made. Furthermore, ETABS software has been applied to assess the structural design of the building. The analysis methods have helped to draw the results and validation of the prototype design.

ASPECTS OF IFD SYSTEM

Industrial, flexible and demountable systems (IFD) imply to easy change and adaptation of buildings while reducing resource depletion and construction cost (Bon and Hutchinson, 2000; Ball, 2002; Kohler and Hassler, 2002; Gallant and Blickle, 2005). Such an approach focuses on the long-term performance of building structures and materials, which attempts to introduce flexible building concepts using industrially produced and demountable systems (Durmisevic, 2006).

Industrial way of construction

Industrial way of construction is to produce building elements in a non-project related manufacturing, under controlled circumstances and in a repeatable process (Zegers and Herwijnen, 2004). International Council for Research and Innovation in Building and Construction, Work group 24 (CIB W24) has defined the Industrialized Building as a building technology in which modern systematized method of design, production planning and control as well as mechanized and automated manufacture are applied. In this case, the elements can be used in several buildings with different characteristics to reduce the cost of manpower and time consuming activities. The quality of the building parts will be controlled in the manufacturing and assembly process either in the factory or the building site. Furthermore, the repeatability of the process makes the manufacturing easier and faster (Hamid et al., 2008). However, industrialized building is not necessarily equal to mass production. Industrial production of the components will increase the opportunities for flexible application.

Flexible design

Flexible building parts require adapting to change according to users' needs easily. During the life of the building, changes will be required according to users demand or to facilitate other functionalities (Slaughter, 2001). Rather than this, new technologies or regulations might be introduced. In fact change is an obvious and inevitable characteristic of built environment and requires sufficient attention at the initial design phase (Brand, 1994; Greden, 2005).

So, it is necessary to provide the building that would be able to change the layout and using materials to meet the new requirements. The importance of this trend is that extending the useful life of existing buildings and constructed systems through accommodating change easily, fast, and inexpensively. It will also improve the value of any property by making it as an investment opportunity (Slaughter, 2001; Morgan and Stevenson, 2005). On the other hand, it supports the key concept of sustainability by lowering material, transport and energy consumption as well as waste and pollution (Gregory, 2004; Bullen, 2007).

Demountable system

Non-recyclable building materials are major part of present waste while large parts of the recycled materials are limited to low quality use or even land fill, because of the high amount of contaminants (Durmisevic, 2006). This is because in current construction, components and structures are not designed to be separated or applied in new buildings. In order to overcome the waste issues, more productive design approaches need to be taken that would simplify dismantling of high value materials for reuse and recycle (Chini, 2002). Demount-ability enables the building parts with various life spans to be separated with little damage to other building parts and suited to be reused or recycled. Indeed, design for dismantling encourages the application of recyclable materials as well as simplifying the separation of materials before or after demolition (Dorsthorst and Kowalczyk, 2002). Therefore, it will extend the life of the building as a whole.

Innovation in the construction industry defines the process of development and application of technologies in a new or improved service to increase productivity and user's satisfaction (Egmond and Scheublin, 2005). However, a higher degree of prefabrication needs more work on design and planning process of the whole construction as well.

Description of the designed IFD terrace house

A two story terrace house has been proposed for the prototype unit of study. The lot size was considered as 18600-7800 mm while the interior architectural design attempts to create configuration that encourages the possibility of future adaptations for the spaces use (Figure 1). Therefore, the unusable or single function spaces like circulation and fixed element have been minimized. The plans, section, and elevation have been framed from a modular grid which is based on the available standard sizes (Ministry of Housing and Local Government Malaysia, 2009). The grids will allow simply reducing or expanding the design based on the site restrictions. The size and location of the fenestrations and doors have also been defined according to modular

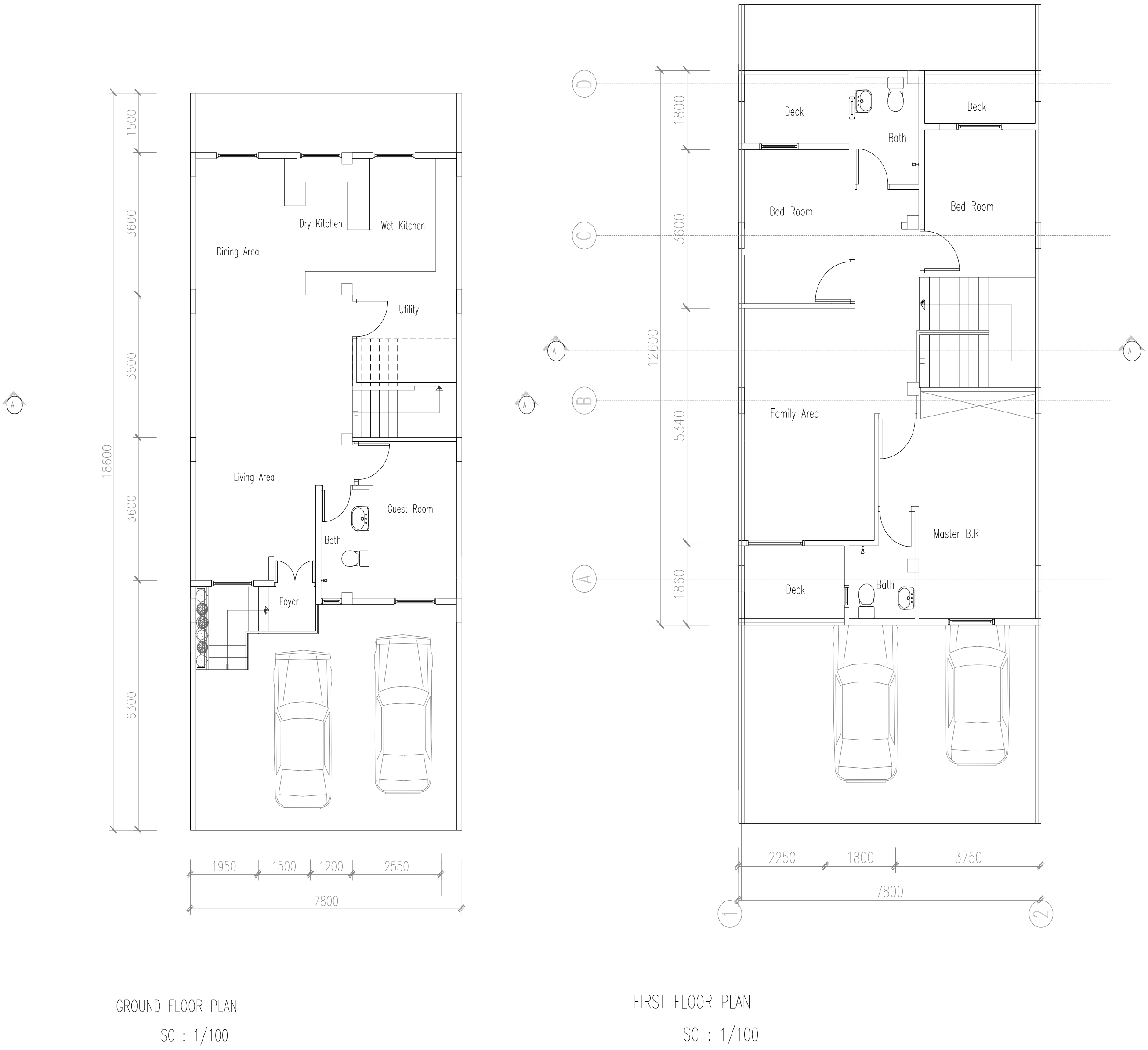


Figure 1. Prototype terrace house, design concept plans, section and elevation.

design rules and can be changed flexibly.

Partition walls were considered as, 600 mm × 400 mm ×100 mm, concrete panels. The constructability of the walls using the panels is an important factor considered in the development of the panels. Since, the main walls in front and rear façade have considered as non load bearing, the main requirements for the interlocking panels are the stability and transferring the weight load to the beams and columns. The panel dimensions followed modular design ruels, accordingly, other spaces in the house also are in conformity with modular dimensions, therfore encouraging the application of other modularly coordinated components such as doors and windows. Since the typical room height of 2800 mm has been adopted, the application of half or broken block for fitting into the space will not be required. Consequently, no wastage of materials will be provided and exact number of panels that will be required for a specified house could be apprised from the architectural drawings.

The following features are sought to be included for the component adoption:

(i) Efficient interlocking mechanism in various directions.
(ii) Meeting modular coordination requirements, that is, the dimensions are fit into the modular dimensions and horizontal planning dimensions of 3 M and vertical planning dimension of 1 M, where 1 M = 100 mm.
(iii) Dry and fast construction with minimum in-situ casting.

Table 1. Description of the structural elements for the pattern IFD terrace house.

S/N	Element	Description
1	Main load carrying system	Moment resisting frame
2	Foundation	Strip footing with pedestal
3	Pedestal (1)	Square column (450-450-1200 mm) Component code: STR-KP-T-SC-450
4	Pedestal (2)	Square column (600-300-1200 mm) Component code: STR-KP-T-SC-600
5	Roof system	Light weight prefab panels
6	Floor system	Hollow core slab Component code: STR-KP-L-HCS-150
7	Beam (1)	Rectangular Beam (150-500 mm) Component code: STR-KP-R-RB-150-R
8	Beam (2)	Rectangular Beam (300-500 mm) Component code: STR-KP-R-RB-300-R
9	Column(1)	Square column (150-600 mm) Component code:STR-KP-T-SC-150
10	Column(2)	Square column (300-300 mm) Component code:STR-KP-T-SC-300
11	Panel(1)	Non-load bearing Concrete panel (600-100-400 mm) Removable *
12	Panel(2)	Load bearing concrete panel Fixed

*These panels are considered non-load bearing in order to maintain the ability of dismantling and rearranging the wall panels.

(iv) Reduce formwork for construction, so make it more environmentally friendly.

Table 1 is presenting the main structural elements of the designed housing unit. Except the proposed panels, other elements' characteristics are according to standards available in 'Modular Design Guide' and components available in IBS catalog booklet (Ministry of Housing and Local Government Malaysia, 2009).

EVALUATION METHOD

Few of the existing modern buildings have been deliberately designed for flexibility which results in difficult process for assessment of that flexibility over time (Davison et al., 2006). Basic principles of the prototype design were to apply high degree of industrialization during construction, flexibility during the installation, and demountability at demolition time.

First step of evaluation

Technical requirements of IFD building design parameters were identified (Gassel, 2003; Zegers and Herwijnen, 2004; Holtz, 2006).Accordingly, the developed prototype has been assessed for its IFD characteristics. The key design parameters are presented in Table 2.

Simulation

In the next step of evaluation, a simulation analysis was run to assess the house layout design. ETABS2000 Extended 3D Analysis of Building Systems (Version 9.0.4) has been used to analyze the structural design of the building. ETABS is well known structural software that utilizes Finite Element Method for analysis of common structural systems (CSI, 2005). It is equipped with steel and concrete design modules which had been used for design of main load carrying elements. Graphical representation of model and loading is also provided (Ghoulbzouri et al., 2009). It is used in our analysis for its relative ease of use, detailed documentation, flexibility and vastness of capabilities.

Applied code

For concrete structure and foundation design, UBC97 has been employed.

Material properties of the main structure (columns, beams and pedestals)

(I) Main compressive strength of concrete = 10 MPa.
(II) Weight per unit volume = 1200 kg/m^3.

Table 2. Definition of IFD characteristics for the panel system.

IFD criteria	Design characteristics
Industrial	
Standardize parts	The whole layout consists of subparts that are manufactured in series
Modular system	All the dimensions are according to Modular system coordination
Reduce number of parts	Consist of small number of parts
Simple assembly protocol	The parts can be assembled on site by means of simples actions and lightweight equipments
Reduce waste	Produces little waste during manufacturing and assembly on site
Changeable	Standard components can be changed during the service life
Flexible	
Freedom of design	Small and changeable parts provide free and adaptable design
Adaptable during assembly	Is not depending on a strict assembly planning
Independence of disciplines	Installation process, bearing structure, outer shell, and interior finishing can be performed independently but combined at the end
Changing of layout	Possibility of changing the layout with little disturbance to other parts of the building
Layout freedom	Open and free interior spaces for future adaptation
Adjustability of building parts	Bearing structure: prefab elements have limited adjustability Installation : dry connections make the installation practically adjustable Outer shell : light panels with dry connections Interior finishing : modular design and adjustable
Demountable	
Reuse from other buildings	The prefab components can be used from other buildings without alteration
Dry connections	Application of dry connections for joining the panels, column, roof, and floor
Demounting of parts	Can be demounted with little disturbance to the other parts
Demounting without waste	Demounting will not cause waste production
Reuse of materials	Elements' materials can be used as new raw materials
Reuse of building parts	One building component can be reuse in the other buildings

(III) Mass per unit volume = 1200 kg/m^3.
(IV) Modulus of Elasticity = 5800 MPa.

Loading

The applied loads have been calculated for two story residential building construction. The loads have been determined according to project specification for dead, live and earthquake loads.

a) Dead load

Weight of the floor is taken as 425 kg/m^2, which is according to the standard specifications of prefabricated concrete slabs.
(I) Weight of roof is taken as 100 kg/m^2 (Light ceiling is considered).
(II) Distributed partition walls without openings' weight have been considered as 420 kg/m (for 2.8 m Height walls) and opening effects has been considered in walls that have window. These loads are assigned in the parts that were needed.
(III) Framing and external walls weight was computed in ETABS2000 program.

b) Live load

(I) Live load of floor is taken as 200 kg/m^2.

c) Earthquake load

Earthquake coefficient has been considered as 0.08. ETABS has the ability to calculate the shear stress according to the considered earthquake coefficient, DL, LL, and elements' weight. This stress will be assigned between the nodes by ETABS.

Modeling and analysis

a) Framing and element section assignments

The grid lines, beams and column elements have been defined and drawn according to the architectural drawings in the first step of modeling. Afterwards, the

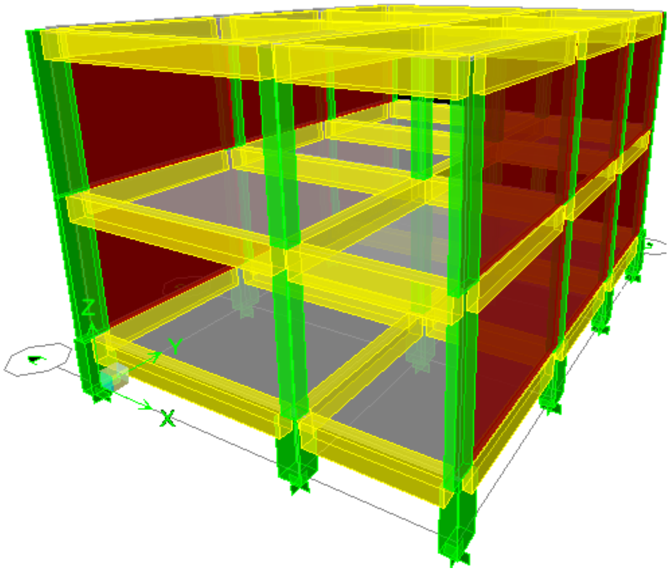


Figure 2. General 3D view of the model.

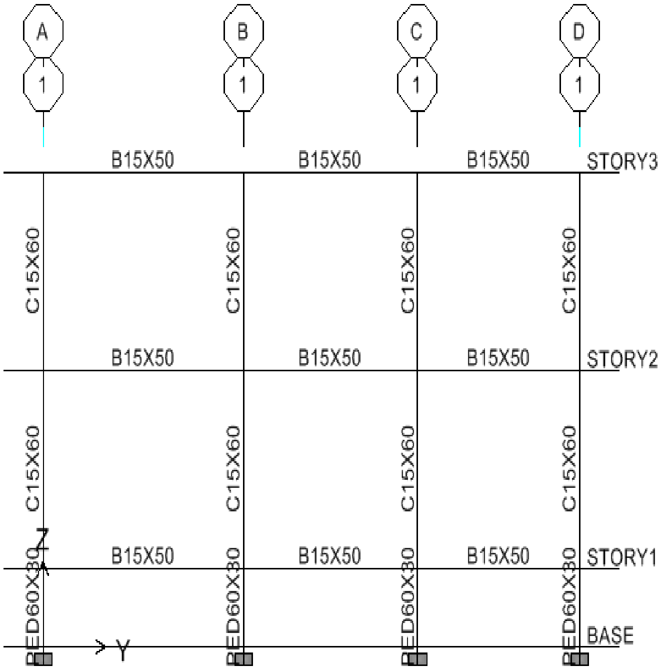


Figure 3. Framing view axis 1-1.

considered sections have been defined and assigned to each related element. The graphical representations of the model are shown in Figures 2-5.

b) Loading and load combinations according to UBC97 Code

In this step, the assumed loads have been assigned to each element (except the elements' self weight that will be considered by ETABS). The load combinations for the three main loads; Dead Load (DL), Live Load (LL), and Earthquake Load (EQ) at X and Y direction, have been determined according to UBC97 Code as follows:

(I) 1.4DL
(II) 1.4DL +1.7 LL
(III) 1.32 DL + 1.1 EQX + 0.55 LL
(IV) 1.32 DL - 1.1 EQX + 0.55 LL
(V) 1.32 DL + 1.1 EQY + 0.55 LL
(VI) 1.32 DL - 1.1 EQY + 0.55 LL
(VII) 0.99 DL + 1.1 EQX
(VIII) 0.99 DL + 1.1 EQX
(IX) 0.99 DL + 1.1 EQY
(X) 0.99 DL - 1.1 EQY

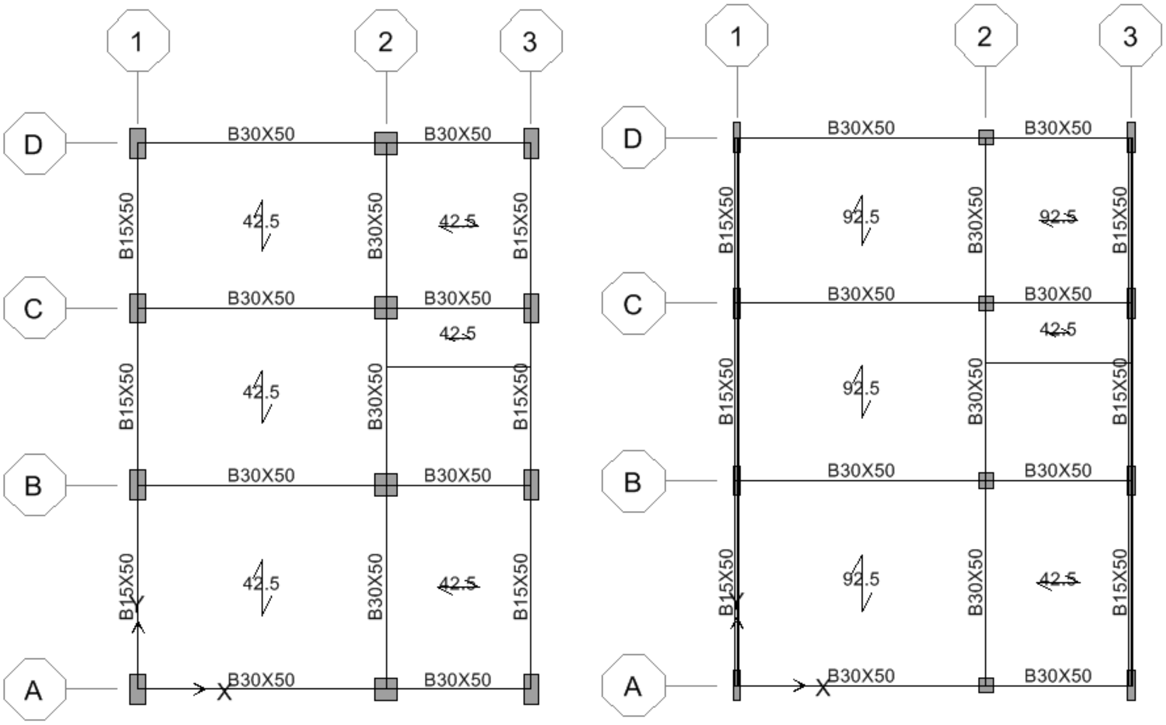
c) Analysis and Design

The concrete structure has been analyzed by ETABS2000 Ver. 9.0.4. The analysis creates reliable estimation of the internal forces, stress, deformations, and behavior of the structure under the appointed loads or movements and consequently guides for safe design of the structures. The three main outputs include the "Shear Forces/Stress", "Moment Forces/Stress" and "Axial Forces/Stress". Each force is available for a special load case, combination or envelope of combinations. Some graphical outputs of the sample's frame under envelope of load combinations are shown in Figure 6.

In the next step, the internal forces were extracted and applied for the design and checking of the sections and structural elements according to the UBC97 Code. Subsequently, the capacity for each column and applied stress were compared. The comparison is produced in graphical and numerical method using capacity ratio of the section. If this ratio is greater than 1 it means that the section is over stressed and needs strengthening. The results from analysis illustrated that the capacity ratio for all columns in the model were smaller than 1. Figure 7 displays one sample section for the capacity ratio of the model.

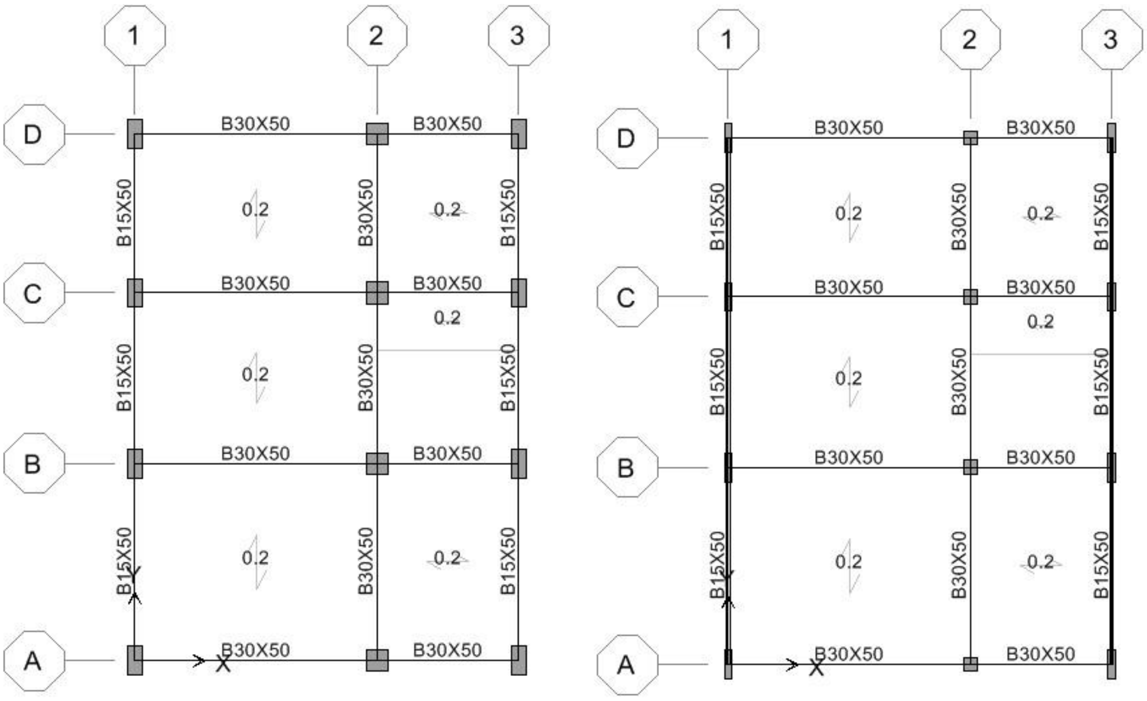
Furthermore, results from Column P-M-M Interaction Ratios shows that the ratios of existing loads to the capacity of the columns are less than 1.0 in all the stories ETABS controls the capacity of beams according to the internal stresses. The required reinforcements according to the defined beam size and materials (concrete and bars) specifications would be recognized. For this study the results were be compared with prefabricated elements and the optimum sections were chosen accordingly (Figure 8). It means that the assigned prefabricated columns and beams have the capacity to tolerate the existing loads.

Member deflections and story drift are other important parts of the structural design which were checked



(a) **(b)**

Figure 4. First (a) and second (b) floor dead load.



(a) **(b)**

Figure 5. First (a) and second (b) floor live Load.

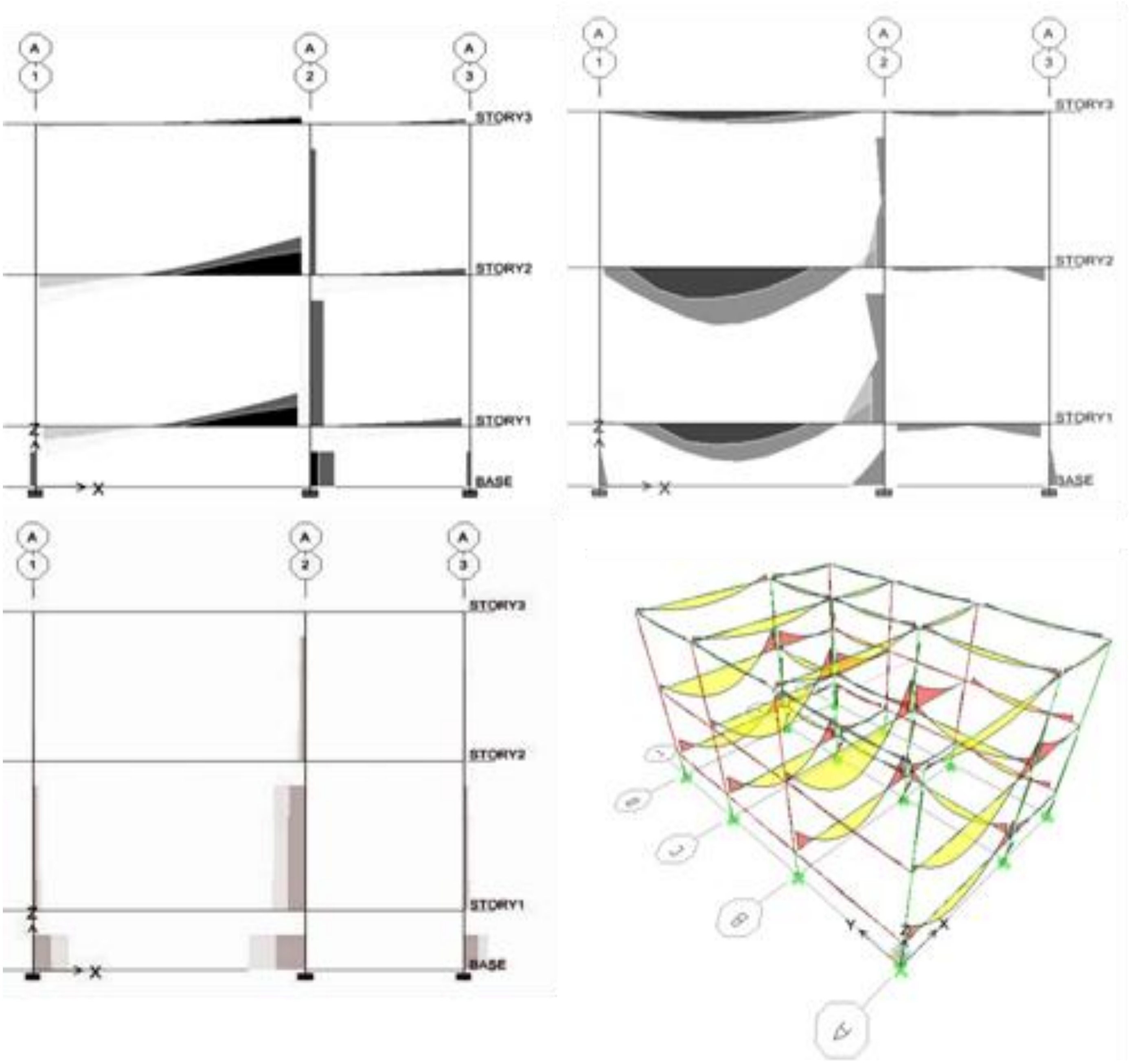


Figure 6. Graphical analysis of the structural frame under load combination.

according to the designing code. Deformed shape of the structure after applying the loads is illustrated in Figure 9. Subsequently, the vertical and horizontal replacements of the beams and columns have been controlled according to ETABS output results and UBC97 criterion.

Figure 10 shows the support reaction driven from the ETABS output files. This evaluation will be applied for future footing design.

Finally, Beam/Column Capacity Ratio was checked in order to obtain the optimum sections.(6/5) Beam/Column Capacity Ratios, shows that the ratio of beams capacity to columns capacity is less than 1.0 in all stories. Figure 11 displays two sample elevations for clarification.

d) Previous studies

Various researchers have applied ETABS software for analyzing the structural elements of the medium and high rise building. Results from similar studies reveal the

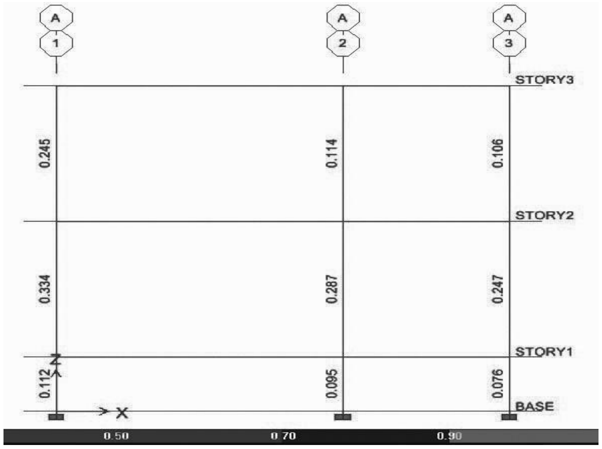


Figure 7. Section from Column's internal forces in the double story sample building.

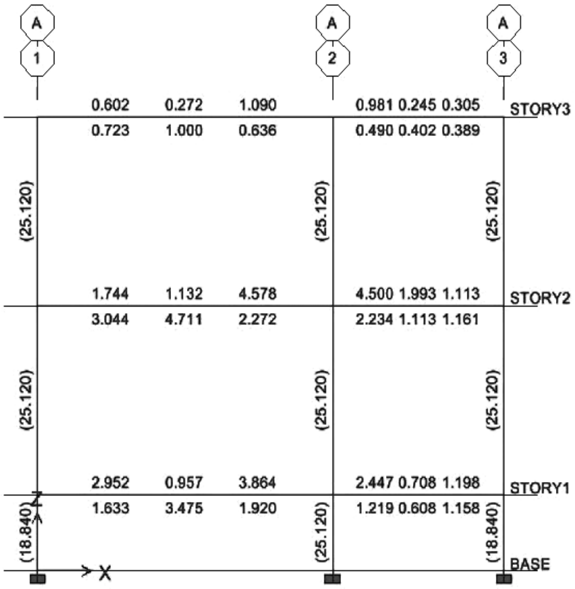


Figure 8. Section from longitudinal reinforcing**.**

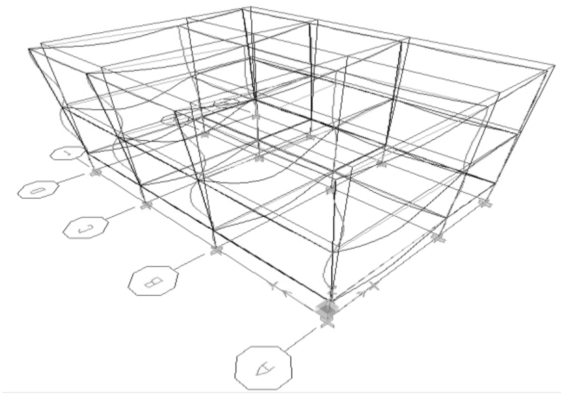


Figure 9. Deformed shape of the structure.

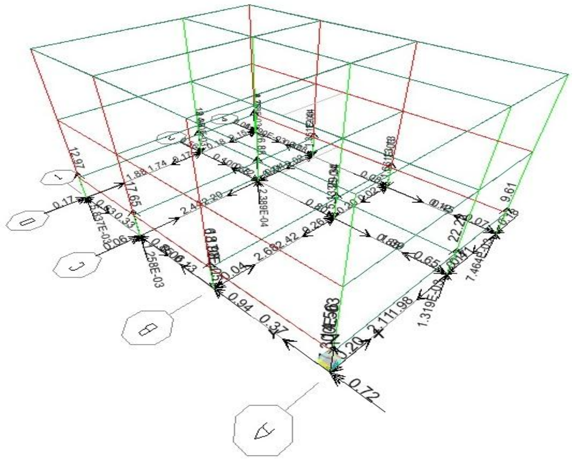


Figure 10. Support reactions for the columns.

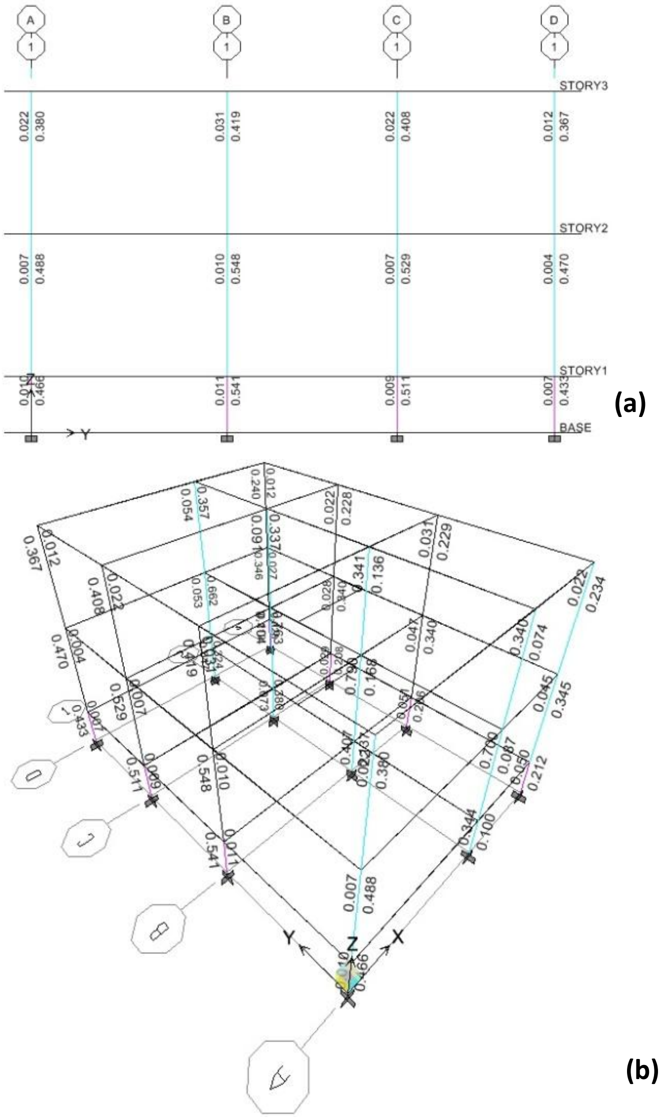


Figure 6. (6/5) Beam/Column Capacity Ratios.

applicability of the software and supports the findings from current study.

Kilar and Fajfar, (1996) have analyzed the structure of the seven story reinforced concrete frame-wall building using ETABS. They discussed that asymmetric structures require larger displacements and ductility to develop the same strength as in the symmetric structure remarkably at the flexible side of the building. In fact, at the same displacement, the strength of the symmetric structure is bigger than the strength of the asymmetric one.

Henry (2006) analyzed the flexural and shear capacity of a 5 story office building with ETABS. The study revealed that the critical shear stress from moment transfer in the interior columns were exceed. Consequently, the interior columns under greater lateral loads were upsized to intensify the shear perimeter and reduce shear stresses.

Conclusions

Passive design of the house and application of new construction techniques will make it suitable for current and future requirements of the occupants and the community. This objective can be achieved by using durable materials and fabricated systems, as well as designing flexible and cost-effective layouts to fulfill changing requirements of the occupants and their life style.

This paper presents the process for development and assessment of IFD building components. In an attempt to evolve a new and innovative system, a number of criteria have been studied for the theoretical performance as well as simulation analysis for the structural performance. The main features of innovative layout design are:

- The dimensions satisfy the modular coordination requirements.
- The simple shape of the components will result in easy production and easy assembly of the building.
- The interlocking and connection mechanism will help for efficient assembly.
- Self-aligned construction system ensures accurate and fast construction.

Feasible IFD design requires encouragements such as specific assessment tools for measuring deconstructability of the building elements as well as governmental policy supports for reducing cost and environmental effects. The offered design needs still further development and the detailing principles that will be set up in the next steps of the study.

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