Numerical modelling and cost-duration analysis of roof structure design changes

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Abstract. Determining building design and type of material is very important before initiating a construction project because structural design changes can impact the project’s cost and duration. This study will discuss the impacts of such changes in building design, both on structure and on cost and duration. It will focus on a case study of a showroom office building that intends to change the design of its roof from concrete to steel frames. The research will be carried out using the Finite Element Method numerical modeling, as well as cost and duration analysis. The use of steel frame may shorten the construction duration while the use of concrete roof may lower the cost.

Keywords: Roof structure, cost, duration, numerical modelling, concrete, steel

1. Introduction

Building construction is one of the most important activities for the national economy due to its ability to absorb a huge amount of resources. Hence, it requires good planning of resources including building materials. An early decision on material selection, for example whether to use steel or concrete, significantly impacts the entire project. The impacts can be seen especially on costs such as construction cost and maintenance cost, as well as on durability and building appearance.

The roof is a crucial building element since all the rooms underneath it can be covered and protected against rain, heat, and dust from outside the building [1]. Furthermore, Maulana [2] explains that the roof functions more specifically to carry its own weight from the roof material, withstand the force of the wind coming from the horizontal direction, receive heat from the sun, keep the temperature in the rooms and avoid the entry of rain water.

There are several types of roofing used in Indonesia. Some that are often used are lightweight steel roof truss, wooden roof truss, and concrete roof. Lightweight steel roof truss and wooden roof truss are similar in design because they both implement a truss structural system (frame), the only difference is in materials. Usually, modern buildings use lightweight steel frames because steel is a relatively more durable material than wood, which is easy to rot when exposed to water and air for a certain amount of time. In addition, according to Yusuf [3], it is currently quite difficult to find workers who are experts in making connections for wooden frames rather than steel. Lastly, a roof using concrete as its main
material is similar to a steel frame roof and is also pretty much used in buildings today. Most of the concrete roofs that we saw are flat.

The benefits of concrete roof come the fact that its structure is formed with concrete material. Some of these benefits are [4] economical, conformity between structural and architectural design, fireproof, rigidity, and material availability. However, concrete material also has several disadvantages [5] namely low tensile strength (reinforcing steel needs to be installed to provide greater tensile strength), difficulty to be perfectly waterproof, not ductile (brittle) in its normal state, expanding and shrinking upon changes in temperature, the need to dilate (expansion joint) to prevent cracks due to temperature changes, relatively low strength per unit weight or volume, only 10% compressive strength compared to the strength of steel while its specific gravity is about 30% compared to the specific gravity of steel, and longer construction time (for working with in-situ cast slabs, scaffolding installation, formwork and reinforcement [6]).

Meanwhile, the advantages of steel roof are quicker execution, ease to modify in case of structural changes in the future, environmentally friendliness, and ease to design. However, steel has several disadvantages when used as a structural material for roofing: corrosive [7], low fire resistance [8], weak in facing compression loads [9] and need for additional finishing [10].

Different materials chosen in building construction will result in different work duration and project cost calculation. The duration of each activity can be calculated using a number of factors including the experience of the project manager, the use of company-specific standards, the production data from subcontractors, and the productivity data from each worker [11]. In this study, the calculating method used is a quantitative calculation based on workers’ productivity, which is obtained through the coefficient standard set by the Ministry of Public Works of the Republic of Indonesia in the Analysis of Public Work Unit Prices in Ministry Regulation PUPR No. 28/PRT/ M/2016. Based on the Minister’s regulation, the formula for calculating the duration of work is as follows:

\[
\text{Durations} = \frac{\text{Unit} \times \text{Coefficient}}{\text{Number of Workers} \times \text{Total Work Hours in a Day}} \quad [\text{days}]
\]

The estimated cost uses a unit price analysis of work that has been set in Ministry Regulation PUPR No. 28/PRT/ M/2016. This unit price analysis can be made after several stages, namely determining the scope of work, preparing WBS, risk analysis, determining construction methods, and determining resource requirements. The results of this unit price analysis will serve as an input to create a budget plan as the price per unit volume of work.

Several studies have been conducted related to comparative studies of steel and concrete materials in construction, including the evaluation of costs between steel and concrete cast-in-situ in Sri Lankan building construction [19], the evaluation of cost between steel and concrete in commercial building construction [18], and an evaluation of environmental impact between steel and reinforced concrete in bridge structures [20]. Therefore, the novelty of this study is to evaluate alternative designs between steel and concrete materials for construction buildings and considering earthquake loads. The research is more focused to the roof structure of buildings and evaluating the cost and project activity duration.

In this research, the use of steel to replace concrete material for roof frame will be evaluated in terms of strength, duration, and cost of the project. Conventional concrete construction requires additional material namely formwork as a mold, whereas steel construction does not. Steel as a structural component can be fabricated outside the site area so that only appointment (erection) and installation of the connection need to be carried out at the site. In addition to the cost saving from the lack of formwork needed, the use of steel can understandably accelerate construction. However, steel is more expensive than concrete.

2. Research Methodology

The descriptions of the concrete roof and steel frame roof structural conditions are obtained through structural modeling. The two models are then compared in terms of structural efficiency by assessing
the estimated duration and cost based on data also obtained from the modeling. Numerical model is made using the finite element method. The cost and duration comparison also consider the differences in volume and method of work. It will be made using the work unit price analysis and the duration estimation method obtained from literature review.

3. Structural Models

3.1 Concrete Roof Modelling

The concrete slab used has a thickness of 120 mm with a concrete quality of K-300 (fc’ = 24 MPa).

The concrete roof uses 200mm X 300mm rectangular roof beam. The roof beam uses the same quality concrete as the concrete beam, which is fc’ 24 MPa. The highest upper support reinforcement demand value is 931 mm$^2$ while the largest lower support reinforcement demand value is 427 mm$^2$. The lower middle span reinforcement demand value is 447 mm$^2$ while the value of the upper middle span reinforcement demand is 206 mm$^2$. In addition, the biggest shear reinforcement requires 388.21 mm$^2$.

Meanwhile, for concrete roof calculation is performed manually based on the largest moment at the edge and middle span. For one slab measuring 5 m x 5 m in the x direction, the greatest moments at support and mid-span of the structure are 14.2 kNm and 11.2 kNm. As for the y direction, the largest moments at support and mid-span of the structure are 31.5 kNm and 14 kNm. These moments produce reinforcement x direction of D13-250 mm, field direction x of D13-330 mm, direction y of D13-120 mm, and pitch direction y of D13-250 mm.

3.2 Steel Roof

Four steel roof models were created to look for the most efficient design to be compared to the concrete roof. The four designs themselves went through a series of load testing via the Finite Element Analysis to ensure safety when applied. Load testing is done by looking at the results of the demand per capacity ratio (DCR) and deflection on each bar. DCR illustrates the ability of the building structure under review to face the burden given [13]. Mathematically, DCR can be determined through the following equation.

$$\text{DCR} = \frac{Q_{ud}}{Q_{ce}} \leq 1$$  \hspace{1cm} (2)

In this equation, Qud is the force or load applied to the structure (it can be moments, axial forces, shear, and possible combinations of forces) and Qce is an estimate of the maximum capacity of the structural components. If the DCR value exceeds 1, then the structural component under review is likely to experience excessive stress, which can result in structural failure.
Because the building object under this study does not have a symmetrical shape, each design will subsequently produce two designs, namely Steel Roof 1 with a shorter span and Steel Roof 2 with a longer span.

The result of finite element analysis after modelling the 4 steel roof designs can be found in Table 2.

Table 2. Recapitulation of all Steel Roof Designs

| Design Code | Steel Roof Type | DCR  | DCR Limit | Deflection (mm) | Deflection Limit (mm) | Cross Section | Total Weight (kg) |
|-------------|-----------------|------|-----------|-----------------|-----------------------|---------------|-------------------|
| Design 1    | Steel Roof 1    | 0.926| 0.95      | 2.30            | 37.5                  | WF 250 X 250  | 12.720            |
|             | Steel Roof 2    | 0.570| 0.95      | 5.10            | 54.0                  | WF 350 X 350  | 31.241            |
| Design 2    | Steel Roof 1    | 0.698| 0.95      | 4.10            | 37.5                  | 2L 200 X 200  |                  |
|             | Steel Roof 2    | 0.419| 0.95      | 0.80            | 54.0                  | 2L 250 X 250  |                  |
| Design 3    | Steel Roof 1    | 0.450| 0.95      | 8.10            | 36.0                  | WF 150 X 150  | 4,693.5           |
|             | Steel Roof 2    | 0.926| 0.95      | 27.4            | 51.7                  | WF 150 X 150  |                  |
| Design 4    | Steel Roof 1    | 0.375| 0.95      | 12.2            | 36.0                  | C 200 X 90    | 4,514.7           |
|             | Steel Roof 2    | 0.785| 0.95      | 14.0            | 51.7                  | C 200 X 90    |                  |

Table 2 shows that design 4 is the lightest among all others. This is because the use of the C 200 X 90 channel profile for all the horses is considered quite mild among the other profiles. The key to the efficient design of 4 is the slope angle of the horses which is smaller than design 1 and design 2. Mathematically, it can be formulated as follows:

\[
\text{Pcr} = \frac{\pi^2 E I}{(K L)^2} \tag{3}
\]
In this equation, $E$ is the elastic modulus of steel, $I$ is the inertia of the cross section, $K$ is the factor of effective length of the steel, $L$ is the length of steel span, and $P_{cr}$ is the critical tension strength of the steel. This equation shows that the tension strength of steel is directly proportional to the inertia of the cross section and inversely proportional to the length of the steel span. In other words, the cross-section inertia is directly proportional to the length of the steel spans. That is, the longer the steel span, the greater the cross-sectional inertia needed to be able to produce a certain strength. The need for greater cross-sectional inertia here means greater cross-section steel profile [14]. By reducing the angle of steel from $20^\circ$ to $10^\circ$, the span length can be reduced. In the steel roof 2 with a length of 18.5 meters and an angle of $20^\circ$, the length may be reduced to 12.4 meters if given an angle of $10^\circ$ slope. With the reduction in span length, the magnitude of the cross-sectional inertia requirement is reduced; therefore, the author can use a smaller profile here.

With the same size, the WF profile has the greatest inertia due to the greater number of wings than other profiles such as elbows, canals, and T. However, because it reduces the slope, the span length is also reduced and finally allows the use of profiles smaller than WF profile, namely channel-C profile. Therefore, design 4 is lighter compared to design 3 which uses WF profile, even though it has the same angle.

In addition, reducing the slope also means reducing the height of the building. The reduced height of the building indirectly minimizes the impacts of lateral loading due to the earthquake. In addition, the smaller building angles can reduce the impacts of wind pressure.

However, there is one concern when making a long reduction to the steel span, namely deflection. As shown in Table 2, after reducing the span length, there is also a decrease in the deflection permit limit. For example, long span horses which have a deflection permit limit of 54 mm at a slope of $20^\circ$ are reduced to 51.7 mm at a slope of $10^\circ$. This is in accordance with SNI 1729:2015 (Indonesian National Standard) that the allowable deflection is directly proportional to the length of the steel span [15]. The use of steel profiles with smaller cross sections allows for greater deflection impact.

Although structurally this design is the most efficient, there are still other things that building designers must consider in determining which design to build, such as architectural, comfort, aesthetics, and others beyond the scope of this study. For example, there are concerns about the potential for roof leakage in the future because the slope angle reduction may mean that rainwater need more time to flow downward. Therefore, it is advisable to choose a good quality roof covering and perform periodic roof maintenance [16].

4. Cost and Time Analysis

One method to see the efficiency of a building structure is by comparing the weight of each with its ability or carrying capacity of the burden [17]. The statement may be applicable when comparing the structure of same type buildings, as did the author when determining the most efficient steel roof design. If two structural models with different properties and ways of working are to be compared, the comparison becomes disproportionate. Therefore, another way to look at the efficiency level of each model is to compare cost and duration, rather than just looking at the weight of the building.

In terms of cost, concrete roof has an 11% lower construction cost compared to steel roof with design 4, while in terms of duration, steel roofs with design 4 provide workmanship around 30% faster than concrete roof. This is made possible by the building weights increase. When a building uses a concrete roof, the total weight of the building as a whole (measured through a combination of dead load + 0.25 x live load) is 6855.51 kN. Whereas when using steel roofing, the total weight of the whole building is 8259.64 kN. This building load addition ultimately generates the need to enlarge the dimension of some structural components.

Seeing that the impact of the lack of design 4 is quite disturbing for some building users, it is worth trying to increase the roof slope from $10^\circ$ to $20^\circ$. Thus, the author decided to use the roof design with the most efficient $20^\circ$ slope, namely design 1. Design 1 is using steel roofs with steel cross section WF 250 X 250 and WF 300 X 300.
By using the same calculation of cost and duration, and the same construction method as design 4 earlier, the cost of steel roofing works becomes more expensive compared to the cost of working on concrete roofs, with a difference of up to 55%. However, in terms of duration, steel roofs are still 25% faster than concrete roofs. The use of mobile steel cranes as well as the nature of steel that does not require curing, unlike concrete, is the reason why steel roofs can maintain their durability longer. This is also seen in other designs that have insignificant duration differences.

5. Conclusions

The change in design from a concrete roof to a steel roof may require adjustments to the structure of the building underneath during the design process because it is likely that the roof made of steel has a greater weight compared to the concrete roof. The choice of steel roof may provide faster construction time compared to concrete in carrying a similar load. This is possible because the steel roof does not require time for curing unlike as in concrete roof. In terms of cost, concrete roof offers a lower construction cost compared to steel roof. However, the difference in costs between the two materials can be reduced. This depends on the design for each type of roof. Steel roofs with a low angle slope may reduce the cost difference but it carries other consequences with it such as reduced comfort, reduced aesthetics, and the threat of leakage in the future. Conversely, if you choose a steel roof that has a greater angle, then other factors such as comfort will be obtained, but the process becomes more expensive than concrete roof.

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References

[1] Noorlaelasari Y 2010 Modul Ajar Konstruksi Atap Bangunan Gedung (Bandung: Politeknik Negeri Bandung)
[2] Maulana T R 2011 Identifikasi Faktor-faktor Benefit pada Duk Beton yang Berpengaruh Pada Penggunaan Rangka Atap Baja Ringan (Depok: Universitas Indonesia)
[3] Yusuf H 2009 Studi Perbandingan Rangka Atap Baja Ringan Pryda dengan Rangka Atap Kayu Konvensional (Depok: Universitas Indonesia)
[4] Wight J K and MacGregor J G 2012 Reinforced Concrete Mechanics and Design (New Jersey: Pearson Education Inc.) 6TH ed
[5] Aprilia R 2014 Pelat Beton Bertulang (Balikpapan: Politeknik Negeri Balikpapan)
[6] BSN 2013 Persyaratan Beton Struktural untuk Bangunan Gedung (Jakarta: Badan Standarisasi Nasional) 2847:2013
[7] Shollock B, Thakur D, and Couchman G 2016 Why Steel in Construction J. Materials & Engineering: Propelling Innovation 41 700
[8] Occupational Safety and Health Administration 2015 Fire Service Features of Buildings and Fire Protection Systems (Washington D.C.: U.S. Departement of Labor)
[9] Setiawan A 2002 Perencanaan Struktur Baja dengan Metode LRFD (Jakarta: Penerbit Erlangga)
[10] Weight D 2006 Data: Whole-life costs: Concrete vs steel (Available: building.co.uk).
[11] Baldwin A and Bordoli D 1950 A Handbook for Construction Planning and Scheduling (West Sussex: John Wiley & Sons, Ltd)
[12] Kementerian PUPR 2016 Pedoman Analisis Harga Satuan Pekerjaan Bidang Pekerjaan Umum (Jakarta: Kementerian Pekerjaan Umum dan Perumahan Rakyat)
[13] GSA 2003 Progressive Collapse Analysis and Design Guidelines (Washington D.C.: The U.S. General Services Administration)
[14] AISC 2016 Specification for Structural Steel Buildings (Chicago: American Institute of Steel Construction)
[15] BSN 2015 Spesifikasi untuk Bangunan Gedung Baja Struktural SNI 1729:2015 (Jakarta: Badan Standarisasi Nasional)
[16] Rubiono G and Qiram I 2016 Pengaruh Sudut Kemiringan Atap Seng dan Plastik Gelombang Terhadap Tingkat Kebisingan Akibat Air Hujan Dinamika Teknik Mesin 6 pp. 99-106
[17] Sandaker B N, 2008 On span and space (New York: Routledge)
[18] Corus Construcion and Industrial 2004, Comparing the Cost of Steel and Concrete Framing Options for Comercial Buildings Supporting the Commercial Decision pp. 10-11
[19] Chandanie H and Kandemulla L 2014 Cost Benefits of Steel Compared to In-situ Concrete in Sri Lankan Building. Proceedings of the Seventh FARU International Research Symposium. Moratuwa: University of Moratuwa
[20] Horvath A. and Hendrickson C T1998Steel versus steel-reinforced concrete bridges:Environmental Assessment. J. Infrastruct. Syspp. 111-117