Efficiency and Effectiveness Comparative Analysis of Wide Flange Beams and Cellular Beams in A Case Project United Tractor

Donald Essen and Muhammad Nur Rahman
Faculty of Engineering, Mercu Buana University Jakarta, Indonesia
donaldessenstmt@gmail.com, mnrahman987@gmail.com

Abstract

United Tractors Company will build a sports center building consist of 3 floors using steel structures. Nowadays, limited land is one of the building development problems. The construction of multi-stored buildings is a solution to the limited land problem. The writer has analyzed beam design with a Wide Flange and Cellular system. Focused on the beam element with construction material in the form of steel with steel quality BJ-37, Fy 240 MPa, Fu 370 MPa. The strength and efficiency of the use of steel tonnage were also analyzed. E-Tabs software 2016 used to steel beam structure analysis. In this beam design planning refers to the steel structure planning following SNI 1729: 2015, SNI 1727: 2013, AISC 2010, ASCE 7-10, and also AISC Design Guide 31. The results of manual verification show that the cross-section of WF 400x200x8x13 and CB 250x125x5x8 with a span length of 6 meters is declared to be strong and safe because fill the strong requirements needs to be smaller than the strength of the plan. The efficiency of the use of Cellular Beam was compared to Wide Flange, the longer of Cellular Beam will increase steel tonnage reductions. The percentage reduction in steel weight will continue to increase when the length of steel usage also increases. This concludes that the use of steel length with steel weight reduction will move linearly. Where in this project with a steel beam length of 1439.27m reduction of steel tonnage was at 19.5%.

Keywords: Wide Flange Beam, Cellular Beam, Comparison

1. Introduction

Enthusiastic exercise the employees of PT. United Tractor encourage management to provide sports facilities and infrastructure. Nowadays, limited land is one of building development problem. The construction of multi-storey buildings is the solution. One of important things in construction of multi-storey building is structural planning. In planning a multi-storey building structure basically must following criteria: Strong in holding planned loads, requirements of serviceability, high durability, accordance with the surrounding environment, economical and easy to maintain [5].

In structural planning, it is necessary to analyze the structure of the reaction caused by axial and lateral forces towards building structure. Structural elements must be designed to able carry an overload of a certain amount, outside of the load expected to occur of normal conditions. Spare capacity is needed to anticipate the possibility of overload factors and undercapacity factors [5]. Based of the problem, this paper analyzes the structures that only review the upper structure, which is the beam element. In this discussion, will analyze the beams with a Wide Flange and Cellular system which will be reviewed regarding the strength and efficiency of the use of steel tonnage. Cellular beam is profile steel I with openings on the body part is which is made by cutting standard profile body parts into 2 parts along the span, then separated, shifted and welded back into new shapes (J.P. Boyer, 1964). The results of this process make the steel profile has higher than the beginning, resulting in the addition of inertia. Increasing inertia will increase the ability of the steel. The economic value of profile I can increase, because with the initial profile I the dimensions are smaller and lighter can be formed into a profile that has a higher height [6]. The steel beam structure analysis is based on SNI 1729: 2015 procedures for planning steel structures for buildings. By using the help of ETABS 2016 computer software for structural analysis.

The rules used are the regulations issued are as follows:
- SNI 1729: 2015 Procedures for planning steel structures for buildings.
- SNI 1727: 2013 Minimum load for building construction planning.
- Steel Design Guide 31 - Castellated and Cellular Beam Design.
2. Methodology

Analysis method used in building structure modeling where the planning used two system, Wide Flange beam system and the Cellular beam system. This research method uses case study analysis method. Case study method is in the form of re-planning with a model that is made in accordance with existing building conditions. The research method used has stages of input, analysis and output. At the input stage will be explained about the structure geometry, dimensions, and specifications of structural elements, the determination of the burden of working with 3-dimensional modeling. The stages of analysis include structural modeling using the 2016 ETABS software. The final stage is the output stage which discusses the strength and efficiency of using steel tonnage. The final result of this plan is to find out what is the tonnage ratio of each design and find out which design is the most efficient if applied to this project.

![Research Flowchart](source: Data in research, 2019)
In this study there are 2 types of data, primary data is existing data obtained from the project under study and secondary data from alternative design experiments. The data is then analysed following stages of the research carried out are as follows:

3. Result and Analysis

3.1 Existing Data

In this case referring to for construction (planning drawings) for the beam size of the Ahemce project is as follows:

Table 1. List of Beam Sizes for Construction

| Beam Type | Size (mm) | Beam Type | Size (mm) |
|-----------|-----------|-----------|-----------|
| 1         | WF 800x300x14x26 | 8         | WF 400x200x8x13 |
| 2         | WF 700x300x13x24 | 9         | WF 350x175x7x11 |
| 3b        | WF 588x300x12x20 | 10        | WF 300x150x6.5x9  |
| 4         | WF 600x200x11x17 | 11        | WF 250x125x6x9  |
| 6         | WF 500x200x10x16 | 12        | WF 200x100x5.5x8 |

Source: Ahemce Project Documents 2019
### 3.2 Check Section Strength

#### Wide Flange Beam

| Material Data |  | Cellular Beam |  |
|---------------|---|---------------|---|
| **Material Data**: | | **Top Root Section**: WF 250x125x5x8 | |
| **WF 400 x 200 x 8 x 13** | | **Height**: (dtop = ht) = 250 mm | |
| **Yield stress (fy)** | 240 MPa | **Width**: (bf) = 125 mm | |
| **Height (H)** | 400 mm | **Thick of web (tw)** = 5 mm | |
| **Width (B)** | 200 mm | **Thick of flens (tf)** = 8 mm | |
| **Thick (Flens/tf)** | 13 mm | **Radius (r)** = 12 mm | |
| **Thick (Web/tw)** | 8 mm | **Section area (A)** = 3268 mm² | |
| **Radius of gyration (rx)** | 168 mm | **Moment of inerisa (Ix)** = 35400000 mm⁴ | |
| **Radius of gyration (ry)** | 45.4 mm | **Moment of inerisa (Iy)** = 2550000 mm⁴ | |
| **Momen of inerisa (Ix)** | 23700 cm⁴ | **Radius of gyration (rx)** = 104 mm | |
| **Momen of inerisa (Iy)** | 1740 cm⁴ | **Radius of gyration (ry)** = 27.9 mm | |
| **Section area (A)** | 8412 mm² | **Modulus of section (Zx)** = 285000 mm³ | |
| | | **Modulus of section (Zy)** = 411000 mm³ | |
| **Modulus of section (Zx)** | 1190 cm³ | | |
| **Modulus of section (Zy)** | 174 cm³ | | |
| **Span length (L)** | 6 m | | |
| **Spacing (b₀)** | 2 m | | |
| **Concrete Strength (fc’)** | 30 Mpa | | |
| **Thick concrete** | 170 mm | | |
| **Weight of decks** | 240 kg/m² | | |
| **tc** | 70 mm | | |
| **wr** | 200 mm | | |
| **hr** | 50 mm | | |
| **Ultimite Moment (Mu)** | 48,4101 kN.m → 48410100 N.mm | | |
| **Ultimate Shear (Vu)** | 57,8294 kN → 57829,4 N | | |

#### Figure 7. Ultimate Shear and Moment

Completion:

Assume a = 50 mm and d = 400 mm

As need: \[ M_u \geq \frac{\phi \cdot f_y \cdot (d - a) \cdot (d - a)}{2} \]

\[ = \frac{687.8 \text{ mm}^2}{687.8 \text{ mm}^2} \rightarrow 6.88 \text{ cm}^2 \]

Trying to use wf 400x200x8x13

(As = 84,10 cm²)

Before the concrete hardens, the steel beam carries:

- **Live load during construction**
  
  \[ = 2 \times 100 = 200 \text{ kg/m} \]

- **Dead load**
  
  \[ = 2 \times (240 + 66) = 612 \text{ kg/m} \]

- **qu**
  
  \[ = 1,2(612) + 1,6(200) = 1054,40 \text{ kg/m} \]

- **Mu**
  
  \[ = \frac{1}{6} g_u \cdot L^2 = \frac{1}{6} (1054,4)(6)^2 \]
Wide Flange Beam

\[ M_n = M_p = Z_{cg} f_y = 1190.10^2 \times 240 \]
\[ = 285600000 \text{ N.mm} \]
\[ \phi M_n = 0.9(285600000) \]
\[ = 257040000 \text{ N.mm} > M_u \quad \text{OK} \]

Calculate Flexibility Strength of Composite Beam

After the concrete hardens, load factor borne by the composite beam is:
\[ M_u = 48410100 \text{ N.mm} \quad \text{(data from ETABS)} \]

The width of the effective slab of concrete is taken from the smallest value:
\[ b_E = \frac{1}{4} L = \frac{1}{4} (6) = 1.5 \text{ m} \]
\[ b_E = b_0 = 2 \text{ m} \]

So the width effectively was taken by 1.5 m

Suppose a neutral plastic axis fell on a concrete plate, then the height of strength beam hit on the concrete block was:
\[ A = \frac{A_s f_y (d + t - a)}{0.85 X f_y X b_E} = \frac{8412 \times 240}{0.85 \times 30 \times 1500} \]
\[ = 52.78 \text{ mm} < t_c = 70 \text{ mm} \]

Because \( a < t_c \), means a neutral-plastic axis fell on the concrete plate, and is on the assumption before.

Nominal Flexibility Strength of Composite Beam:
\[ M_n = A_s f_y \left( \frac{d}{2} + t - \frac{a}{2} \right) \]
\[ = 693706169.22 \text{ N.mm} \]
\[ \phi M_n = 0.85 (693706169.22) \]
\[ = 589650243.84 \text{ N.mm} > M_u \quad \text{OK} \]

Next the beams must be checked against the shear:
\[ V_u = 57829.4 \text{ N} \]
\[ \phi V_u = \phi 0.6, f_Y, h, t_w \]
\[ = 0.9(0.6)(240)(358)(8) \]
\[ = 371174.4 \text{ N} > V_u \quad \text{OK} \]

Compactness section check:
\[ \frac{h}{t_w} = \frac{400-2(13+8)}{8} \]
\[ = 44.75 \text{ N} < \frac{1100}{\sqrt{f_y}} = 71 \text{ N} \quad \text{OK} \]

Calculate Need of Shear Stud

Shear connection total number to cause a full composite action

For the full composite action:
\[ C = V_h = 0.85, f_Y, a, b_y = A_s f_y = 2018880 \text{ N} \]

Use the stud 3/4" - 10cm (Asc = 285mm2) One per section.

Reduction factor strength of stud, \( rs \) (\( N_r = 1, H_s = 10 \text{ cm} \))
\[ rs = \frac{0.85 \sqrt{W_s X h_s}}{\sqrt{N_r X h_y}} \left( \frac{H_s}{h_y} - 1.0 \right) \leq 1.0 \]
\[ = \frac{0.85 \sqrt{285 X 50}}{100} \left( \frac{100}{50} - 1.0 \right) = 3.4 > 1.0 \]
Wide Flange Beam

with:
rs = is reduction factor
Nr = Is the number of shear stud on every wave on the cross section of the steel beam.
Hs = Is a high shear stud ≤ (hr + 75mm)
hr = Is nominal high waves of steel deck
wr = Is the width of the effective waves of the steel deck take rs = 1.0. Untuk \( f'_c = 30 \text{ Mpa} \), modulus of concrete elasticity:

\[
Ec = 0.041 w^{1.5} \sqrt{f'_c}
\]

\[
= 0.041(2400)^{1.5} \sqrt{30}
\]

\[
= 26403,49 \text{ MPa}
\]

Shear strength a stud:

\[
Q_n = 0.5 \frac{A_{sc} \sqrt{f'_c}}{V_h} \times E_c
\]

\[
= 0.5 \times (285) \sqrt{\frac{26403,49}{126771,29}}
\]

\[
= 128195,31 \text{ N > Qn OK}
\]

The number of stud required:

\[
N = \frac{V_h}{Q_n} = 15,93 \longrightarrow 16 \text{ stud (for ½ the span)}
\]

For the total length it takes 32 studs for the full composite action to occur. If every 2 waves are installed a stud, then the distance between the stud is \( 2(200) = 400 \text{ mm} \), so the number of stud used is as much (6000 / 400) + 1 = 16 stud, or 8 stud every ½ span.

\[
\sum Q_n = 8(126771,29) = 1014170,35 \text{ N}
\]

Because \( A_{st} * f_y = 2018880 \text{ N} \geq \sum Q_n \), Then there’s part of the profile of steel under pressure.

The balance of force that occurred:

\[
\sum Q_n + Cf = \text{Tmaks} - Cf
\]

\[
1014170,35 + Cf = 2018880 - Cf
\]

\[
2 \times Cf = 1004709,65
\]

\[
Cf = 502354,83 \text{ N}
\]

The location of the neutral plastic axis calculated from above the flens press is:

\[
\frac{Cf}{b_y f_y} = \frac{502354,83}{200 \times 240} = 10,47 \text{ mm ( < tf = 13 mm) }
\]

Ts location, measured from the underedge of steel flens:

| Area, A (cm²) | Arm, y (cm) | A * y (cm³) |
|---------------|-------------|-------------|
| Concrete slab | 2550        | 8.5         | 21675       |
| WF 400       | 84,12       | 48.5        | 4079,82     |

\[
y = \frac{225754,82}{2634} = 9,78 \text{ cm}
\]

Besarnya a dihitung dari persamaan:

### Table 2. Properties Tee Atas di Tengah Opening

| Luas (A) | Traian dari tinggi flens y | Ay | Ay² | Iy |
|----------|----------------------------|----|-----|----|
| cm²      | cm                        | cm²| cm⁴ | cm⁶ |
| Pipa     | 1000.0                    | 0.0| 0.0 | 0.0| 530.3|
| Stens    | 205.1                     | 32 | 10256| 10602658,75| 4042,5|
| Tee      | 1301.5                    | 10256| 10602658,75| 5609,0|

\[
\gamma_{o-t-top-net} = \sum \frac{Ay}{A_{t-top-net}} = \frac{10296.6}{1301.5} = 7.91 \text{ mm}
\]

\[
I_{x-t-top-net} = \sum I_y + \sum Ay^2 - A_{t-top-net} \cdot \gamma_{o-t-top-net}^2
\]

\[
= 966959,5 + 106020658,8 - 1301.51 \times 7.91^2
\]

\[
= 106035894.7 \text{ mm}^4
\]

Properties Tee Above on the Critical Section

The moment of inertia in the x direction - with the radius of gyration assumed to be zero:

### Table 3. Properties Tee Above on the Critical Section

| Luas (A) | Traian dari tinggi flens y | Ay | Ay² | Iy |
|----------|----------------------------|----|-----|----|
| cm²      | cm                        | cm²| cm⁴ | cm⁶ |
| Pipa     | 1000.0                    | 0.0| 0.0 | 0.0| 530.3|
| Stens    | 205.1                     | 32 | 10256| 10602658,75| 4042,5|
| Tee      | 1301.5                    | 10256| 10602658,75| 5609,0|

\[
\gamma_{o-t-top-crit} = \frac{\sum Ay}{A_{t-crit}} = \frac{14021.9}{1354,99} = 10,35 \text{ mm}
\]

\[
I_{x-t-crit} = \sum I_y + \sum Ay^2 - A_{t-crit} \cdot \gamma_{o-t-crit}^2
\]

\[
= 154452,9 + 196613834,3 - 1354,99 \times 10,35^2
\]

\[
= 196623183,9 \text{ mm}^4
\]

Lower Tee Properties in the Middle of Opening

The moment of inertia in the x direction - with the radius of gyration assumed to be zero:

### Table 4. Properties Tee Down at the Middle of the Opening

| Luas (A) | Traian dari tinggi flens y | Ay | Ay² | Iy |
|----------|----------------------------|----|-----|----|
| cm²      | cm                        | cm²| cm⁴ | cm⁶ |
| Pipa     | 1000.0                    | 0.0| 0.0 | 0.0| 530.3|
| Stens    | 205.1                     | 32 | 10256| 10602658,75| 4042,5|
| Tee      | 1301.5                    | 10256| 10602658,75| 5609,0|

\[
\gamma_{o-t-bot-net} = \sum \frac{Ay}{A_{t-bot-net}} = \frac{10296.6}{1301.5} = 7.91 \text{ mm}
\]

\[
I_{x-t-bot-net} = \sum I_y + \sum Ay^2 - A_{t-bot-net} \cdot \gamma_{o-t-bot-net}^2
\]

\[
= 966959,5 + 106020658,8 - 1301.51 \times 7.91^2
\]

\[
= 106035894.7 \text{ mm}^4
\]
Wide Flange Beam

\[ a = \frac{\sum Q_n}{0.85 \times f_L^b \times b_L} = \frac{1014170.35}{0.85 \times 30 \times 1500} = 26.51 \text{ mm} \]

Tentukan momen internal terhadap garis kerja Ts :

\[ \Sigma Q_n : M_{n1} = \frac{\Sigma Q_n (d - \bar{y} + t_s - \frac{a}{2})}{2} = 1014170.35 (400 - 9.78 + 170 - \frac{26.51}{2}) = 465472715.87 \text{ N.mm} \]

\[ C_f : M_{n2} = \frac{502354.83 (400 - 9.78 - 5.23)}{= 193401457.14 N. \text{mm}} \]

\[ M_n = M_{n1} + M_{n2} = 658874173.01 \text{ N.mm} \]

\[ \frac{\bar{O}_b \cdot M_n}{n} = \frac{0.85 (658874173.01)}{= 56043047.06 \text{ N.mm}} \]

\[ = 56.00 \text{ ton.m} > \text{Mu (7.44 ton.m)} \]

Jadi, dapat dipasang 16 buah stud 3/4" - 10 cm dengan jarak 400 mm ( tiap 2 gelombang dek baja ).

Kontrol Lendutan

Sebelum beton mengeras

\[ q_o = \frac{2(240 + 66) = 612 \text{ kg/m} = 6.12 \text{ N/mm}}{= \Delta 1 = \frac{5q_S^4}{384E_{bf}} = \frac{5 \times 6.12 \times 600^4}{384 	imes 200000 	imes 23700 \times 10^4} = 2.18 \text{ mm}} \]

Lendutan akibat beban hidup selama konstruksi

\[ q_L = \frac{2(100) = 200 \text{ kg/m} = 2 \text{ N/mm}}{= \Delta 2 = \frac{5q_L^4}{384E_{bf}} = \frac{5 \times 2 \times 600^4}{384 	imes 200000 	imes 23700 \times 10^4} = 0.71 \text{ mm}} \]

Setelah beton mengeras aksi komposit mulai bekerja, momen inersia penampang komposit Itr dihitung sebagai berikut :

\[ n = \frac{E_I}{E_L} = \frac{200000}{264049.49} = 7.57 \rightarrow 8 \]

\[ \frac{b_L}{n} = \frac{1500}{8} = 187.50 \text{ mm} \]

Luas A ( cm2 )

Pelat Beton = 225

WF 400 = 84,12

\[ \sum = 309,12 \]

Lengan y ( cm )

Pelat Beton = 8.5

WF 400 = 48,5

\[ A \ast y ( \text{ cm3} ) \]

Pelat Beton = 1912,5

WF 400 = 4079,82

\[ \sum = 5992,32 \]

Io

Pelat Beton = 2700

WF 400 = 23700

d

Pelat Beton = 10.89

WF 400 = -29.11

\[ Io + A \ast d^2 = 106035894,7 \text{ mm4} \]

Cellular Beam

Lower Tee Properties In Critical Sections

The moment of inertia in the x direction - with the radius of gyration assumed to be zero:

\[ y_{o-t-bot-crit} = \frac{\Sigma A_{y}}{A_{t-bot-crit}} = \frac{14021,9}{1354.99} = 10.35 \text{ mm} \]

\[ I_{x-t-bot-crit} = \sqrt{\frac{\Sigma I_{y} + \Sigma A_{y}^2 - A_{t-bot-crit}.y_{o-t-bot-crit}^2}{79-(1.035+(0.5 \times 8))}} = 3041344.6 \text{ mm3} \]

Properties Of Net Section at Middle of Opening

The moment of inertia in the x direction - with the radius of gyration assumed to be zero:

\[ y_{steel-net} = \frac{\Sigma A_{y}}{A_{net}} = \frac{336602.5}{2000} = 168.30 \text{ mm} \]

\[ I_{steel-net} = \sqrt{\frac{\Sigma I_{y} + \Sigma A_{y}^2 - A_{net}.y_{net}^2}{79-(1.035+(0.5 \times 8))}} = 212071789.3 + 105566268065 - 2000 \times 168.30^2 = 105722 \times 10^{11} \text{ mm4} \]

Properties Of Net Section di Bagian Kritikal

\[ Anet-crit = A_{t-top-crit} + A_{t-bot-crit} = 1354.99 + 1354.99 = 2709.98 \text{ mm2} \]

\[ d_{effec-noncomp} = d_{g} - (0.5t_{f-top} + y_{o-t-top-crit}) - (0.5t_{f-bot} + y_{o-t-bot-crit}) = 336.6 - ((0.5 \times 8) + 10.35) - ((0.5 \times 8) + 10.35) \]

\[ = 212071789.3 + 105566268065 - 2000 \times 168.30^2 = 105722 \times 10^{11} \text{ mm4} \]

\[ = 212071789.3 + 105566268065 - 2000 \times 168.30^2 = 105722 \times 10^{11} \text{ mm4} \]
| Wide Flange Beam | Cellular Beam |
|------------------|---------------|
| Pelat Beton = 546513,23 | = 307,91 mm |
| WF 400 = 23548336,7 | Properties Of Net Composite in the Middle of Opening |
| $\Sigma = 24094849,93$ | The moment of inertia in the x direction - with the |
| $\bar{y} = \frac{5992.32}{309} = 19.39 \text{ cm}$ | radius of gyration assumed to be zero: |
| Karena struktur dianggap sebagai balok komposit parsial, | Slab transformation: |
| maka momen inersia harus direduksi sebagai berikut: | The effective width of the concrete slab is taken from |
| Iefektif = $I_k + (I_{fs} - I_k) \frac{\Sigma N_n}{c_f}$ | the smallest value between: |
| = 23700 + (24094849,93 - 23700) $\sqrt{\frac{1014170.35}{2018880.0}}$ | $bE = \frac{1}{4} \cdot L = \frac{1}{4} \cdot 6000 = 1500 \text{ mm}$ |
| = 17084407,59 cm^4 | $bE = bo = 1500 \text{ mm}$ |
| Lendutan akibat beban hidup: | $bE$ dipakai = 1500 mm |
| $q = 2(488.4) = 976.8 \text{ kg/mm} = 9.77 \text{ N/mm}$ | Calculating the value "n" |
| $\Delta 3 = \frac{5qL^4}{384EI_{tr}} = \frac{5 \times 9.77 \times 6000^4}{384 \times 20000 \times 17084407.59 \times 10^4}$ | $n = \frac{E_c}{E_E} = \frac{20000}{4700\sqrt{fc'}} = \frac{20000}{4700\sqrt{30}} = 7.77$ |
| = 4.82 mm | Plate equivalent effective width |
| Lendutan jangka panjang akibat beban mati berupa partisi | $\frac{b_E}{n} = 1500 \div 7.77 = 193,07 \text{ mm}$ |
| dihitung sebagai berikut: | Table 6. Properties Of Net Composite in Middle of Opening |
| $h = \frac{1500}{2 \times 8} = 193.75 \text{ mm}$ | $\gamma_{tr-net} = -\frac{\Sigma A y}{2 \gamma_{tr-net}} = \frac{14174556.7}{34822.27} = 407.1 \text{ mm}$ |
| Luas A (cm^2) | $I_{comp-net} = \Sigma I_o + \Sigma A y^2 - A_{tr-net} \cdot \gamma_{tr-net}$ |
| Pelat Beton = 112.5 | = 105722154201.5 + 191602277943421 - 34822.27 \times 407.1^2 |
| WF 400 = 84.12 | = 19170230283235 mm^4 |
| $\Sigma = 197$ | Global and Local Style in the First Opening Top Tee |
| Lengan y (cm) | First opening location: |
| Pelat Beton = 8.5 | $x = e + 0.5Do = 100 + 0.5 \times 200 = 200 \text{ mm}$ |
| WF 400 = 48.5 | Global shear force: |
| $A \times y$ (cm^3) | The shear force that exists at the distance $x$ |
| Pelat Beton = 956,25 | $V_u$ at a distance $x$ |
| WF 400 = 4079,82 | $x = 57418,17 \text{ N}$ |
| $\Sigma = 5036,07$ | Gaya geser nominal pada beton: |
| $I_o$ | $V_{nc} = 3 (hr + tc).(tc).\left(4\sqrt{f_c'}\right)$ |
| Pelat Beton = 1350 | = 3 (50 + 120).120(4\sqrt{30}) |
| WF 400 = 23700 | = 1340824.82 N |
| $d$ | $V_{C} = \phi_{cv} \cdot V_{nc} = 0.75 \times 1340824.82$ |
| Pelat Beton = 17.11 | = 1005618,62 N |
| WF 400 = -22.89 | $V_{net} = V'_c - V_c = 57418,17 - 1005618,62$ |
| $I_o + A \times d^2$ | = 984200.45 N |
| Pelat Beton = 675413,15 | Momen global: |
Δ5 = \frac{5qL^4}{384EI_{tr}} = \frac{5 \times 9.77 \times 6 \times 10^4}{384 \times 20000 \times 1079894.79 \times 10^4} = 0.01 \text{ mm}

Lendutan total yang terjadi:
Δ1 + Δ3 + Δ5 = 2.18 + 4.82 + 0.01
= 7.01 \text{ mm} \leq \frac{L}{240} = 25 \text{ mm} \quad \text{OK}

Dari hasil verifikasi perhitungan manual di atas menunjukkan bahwa penampang WF 400x200x8x13 dengan panjang bentang 6 meter dinyatakan kuat dan aman karena memenuhi syarat kuat perlu (Mu), lebih kecil dari kuat rencana (ΩMn).

Gaya aksial di Tee atas:
Asumsi aksi komposit sudah bekerja, sehingga kedalaman beton yang mengalami tekan, Xc sama dengan:

Xc = \frac{4}{100} \cdot t_c = \frac{4}{100} \cdot 120 = 4.80 \text{ mm}

Kedalaman efektif balok komposit sebagai berikut:
d_{eff-\text{comp}} = d_y - (0.5t_{f-bot} + \gamma_0-t_{bot-crit}) + h_{f} + t_c - \frac{X_c}{2}
= 336.6 - (0.5 \times 8 + 10.35) + 50 + 120 - \frac{4.80}{2}
= 489.85 \text{ mm}

dan gaya tekan pada beton, C1 adalah:
C1 = 0.85 \cdot f'_c \cdot X_c \cdot b_{eff} = 0.85 \times 30 \times 4.80 \times 193.07
= 23632.04 \text{ N}

C1 = \frac{M_u}{d_{eff-\text{comp}}} = \frac{47299705.7}{489.85} = 96559 \text{ N}

C1 yang menentukan:
C_1-\text{statisies} = 23632.04 \text{ N}

Vierendeel momen di Tee atas:
M_{vu-\text{top}} = V_{net} \cdot A_{x-top-crit} \cdot \left(\frac{0}{4}\right) = 948200.45 \times \frac{1354.99}{2709.98} \times \left(\frac{200}{4}\right)
= 23705011.14 \text{ N.mm}

Kuat Lentur Tee Atas di Kritikal Area Yielding:
Mp = M_y = F_y \cdot S_{x-min-t-top-crit}
= 240 \times 3041344.6
= 729922699.6 \text{ N.mm}

Tekuk local penampang Tee:
Persyaratan
\frac{d}{t_w} < 0.84 \sqrt{\frac{E}{F_y}}
| Wide Flange Beam | Cellular Beam |
|------------------|--------------|
| Maka $F_{cr} = F_y$  |
| Momen nominal $M_n = F_{cr} \times S_{y-min-\bot-crit} = 240 \times 3041344,6$  |
| $= 729922699,6 \text{ N.mm}$  |
| Kapasitas Ratio untuk Tee Atas Area Kritikal di Opening Pertama  |
| $\frac{M_{pu}}{\partial M_{cu}} = \frac{23705011,4}{0,9 \times 729922699,6} = 0,04$  |
| $\frac{M_{pu}}{\partial M_{cu}} < 1 \text{ OK}$  |
| Gaya Global dan Lokal di Tee Bawah Opening ke Enam  |
| Lokasi opening ke enam $x = e + 6S + 0,5D_0 = 100 + 6(300) + 0,5(200)$  |
| $= 2000 \text{ mm}$  |
| Gaya geser global :  |
| Gaya geser yang ada pada jarak $x$  |
| $V_u$ pada jarak $x = 22247,2 \text{ N}$  |

Gambar 10. Momen dan Geser Ultimit Pada Jarak $X = 2000 \text{ mm}$

Gaya geser nominal pada beton :
$V_{nc} = 3 (hr + tc). (tc). (4\sqrt{F_t})$
$= 3 (50 + 120). (120). (4\sqrt{30})$
$= 1340824,82 \text{ N}$

$V_c = \Phi_{ev} \cdot V_{net} = 0,75 \times 1340824,82$
$= 1005618,62 \text{ N}$

$V_{net} = V_u - V_c = 22247,2 - 1005618,62$
$= -983371,42 \text{ N}$

Momen global :
Momen pada jarak $x$

$M_u$ pada jarak $x = 21842241,4 \text{ N.mm}$

Gaya aksial di Tee bawah :
Asumsi aksi komposit sudah bekerja, sehingga kedalaman beton yang mengalami tekan, $X_c$ sama
Wide Flange Beam

\[ X_c = \frac{25}{100} \times t_c = \frac{25}{100} \times 120 = 30 \text{ mm} \]

Kedalaman efektif balok komposit sebagai berikut:

\[ d_{eff-comp} = d_g - (0.5t_{bot} + y_{0-t-bot-crit}) + h_r + t_c - \frac{X_c}{2} \]

\[ = 336.6 - (0.5 \times 8 + 10.35) + 50 + 120 - \frac{30}{2} \]

\[ = 477.25 \text{ mm} \]

dan gaya tekan pada beton, \( C1 \) adalah:

\[ C1 = 0.85 \times f'_c \times X_c \times b_{eff} = 0.85 \times 30 \times 30 \times 193.07 \]

\[ = 147700.23 \text{ N} \]

\[ C1 = \frac{M_u}{d_{eff-comp}} = \frac{21842241.4}{477.25} \]

\[ = 45766,47 \text{ N} \]

\( C1 \) yang menentukan:

\[ C_{1-statifies} = 45766,47 \text{ N} \]

Vierendeel momen di Tee bawah:

\[ M_{vu-top} = \]

\[ V_{net} \times \frac{A_{t-bot-crit}}{A_{net-crit}} \times \frac{P_b}{4} = 983371,42 \times \frac{1354.99}{2709.98} \]

\[ = 24584285.39 \text{ N.mm} \]

Kekuatan tarik Tee bawah di area kritikal

\[ P_n = F_y \times A_{t-bot-crit} = 240 \times 1354.99 = 325198,10 \text{ N} \]

Kuat Lentur Tee Bawah di Kritikal Area

Yielding:

\[ M_p = M_v = F_y \times S_{x-bot-crit} = 240 \times 3041344,6 \]

\[ = 729922699.6 \text{ N.mm} \]

Tekuk local penampang Tee:

Persyaratan

\[ \frac{d}{t_w} < 0.84 \sqrt{\frac{F}{F_y}} \]

Maka

\[ F_{cr} = F_y \]

Momen nominal

\[ M_n = F_{cr} \times S_{x-bot} = 240 \times 3041344,6 \]

\[ = 729922699.6 \text{ N.mm} \]

Persamaan Interaksi Untuk Tee Bawah Kritikal Area di Opening 6

Persamaan 1:

\[ \frac{P_n}{0.9M_n} + \frac{8M_{vu}}{9M_n} = \frac{45766.47}{0.9 \times 325198.10} + \frac{8 \times 24584285.39}{9 \times 0.9 \times 729922699.6} \]

\[ = 0.12 \]

Persamaan 2:
Wide Flange Beam

| $\frac{P_u}{M_{wu}}$ | $\frac{M_{wu}}{M_{wu}}$ |
|---------------------|---------------------|
| 45766,47           | 24584285,39         |

\[
\frac{P_u}{M_{wu}} = \frac{2 \times 0.9 \times 325198,10}{0.9 \times 729922699,6} = 0,04
\]

Menentukan (Kontrol)

Nilai max = 0,12 < 1 OK

Gaya tekan Tee bawah di opening pertama

Lihat perhitungan diatas, untuk gaya aksial yang terjadi di Tee bawah opening, Tul, adalah sebagai berikut :

\[
Tul = C_1 = 45766,47 N
\]

Momen lentur di opening kedua :

Lokasi web kedua

\[
x_2 = e + S + 0.5D_0 = 100 + 300 + 0.5(200) = 500 \text{ mm}
\]

Momen global :

Momen pada jarak x

\[
M_u = 36742016,8 \text{ N.mm}
\]

Gambar 11. Momen dan Geser Ultimit Pada Jarak X = 500 mm

Gaya aksial Tee bawah di opening ke 2 :

Asumsi aksi komposit sudah bekerja, sehingga kedalaman beton yang mengalami tekan, Xc sama dengan :

\[
X_c = \frac{9}{100} \times 120 = \frac{9}{100} \times 10,80 \text{ mm}
\]

Kedalaman efektif balok komposit sebagai berikut :

\[
d_{eff-comp} = d_y - \left( 0.5t_f - 0.5y_0 - bot \right) + h_r + \frac{t_c - X_c}{2}
\]

\[
= 336,6 - (0.5 \times 8 + 10,35) + 50 + 120 - \frac{4,80}{2} = 489,85 \text{ mm}
\]

dan gaya tekan pada beton, C1 adalah :

C1 =
| Wide Flange Beam | Cellular Beam |
|-----------------|--------------|
| $0.85 \cdot \frac{F'_C \cdot Xc}{b_{eff}} = 0.85 \times 30 \times 10,80 \times 193,07 = 53172,08 \text{ N}$ | $C1 = \frac{M_u}{d_{eff-comp}} = \frac{36742016,8}{489,85} = 75006,02 \text{ N}$ |
| $C1$ yang menentukan : $C_{1 statistics} = 53172,08 \text{ N}$ | $Gaya Geser Horisontal di Web Post : Vuh = T_{u2} - T_{u1} = 53172,08 - 45766,47 = 98938,56 \text{ N}$ |
| Momen Lentur di Web Post : $Muh = 0.9 \cdot \frac{D_o}{2} \cdot V_{uh} = 0.9 \cdot \frac{200}{2} \cdot 98938,56 = 8904470,05 \text{ N.mm}$ | $Kuat Geser Horizontal Web Post$ |
| $Kuat tekan Tee bawah di opening pertama$ $\theta V_{n-horiz} = \phi_v \cdot F_y \cdot e \cdot t_{w-top} = 0,6 \times 240 \times 100 \times 5 = 72000 \text{ N}$ | $Kuat Lentur Web Post$ |
| Momen lentur elastis : $M_e = t_{w}(s-D_o+0.564D_o)^2 \cdot F_y$ | $Momen tekuk :$ |
| $= \frac{5(300-200+0.564(200))^2}{6} \cdot 240$ | $C1 = 5,097 + 0,1464 \left(\frac{D_o}{t_{w}}\right) - 0,00174 \left(\frac{D_o}{t_{w}}\right)^2$ |
| $= 5,097 + 0,1464 \left(\frac{200}{5}\right) - 0,00174 \left(\frac{200}{5}\right)^2$ | $= 8,17$ |
| $= 1,441 + 0,0625 \left(\frac{D_o}{t_{w}}\right) - 0,000683 \left(\frac{D_o}{t_{w}}\right)^2$ | $C2 = 1,441 + 0,0625 \left(\frac{200}{5}\right) - 0,000683 \left(\frac{200}{5}\right)^2$ |
| $= 1,441 + 0,0625 \left(\frac{200}{5}\right) - 0,000683 \left(\frac{200}{5}\right)^2$ | $= 2,85$ |
| $C3 = 3,645 + 0,0853 \left(\frac{D_o}{t_{w}}\right) - 0,00108 \left(\frac{D_o}{t_{w}}\right)^2$ | $C3 = 3,645 + 0,0853 \left(\frac{200}{5}\right) - 0,00108 \left(\frac{200}{5}\right)^2$ |
| $= 3,645 + 0,0853 \left(\frac{200}{5}\right) - 0,00108 \left(\frac{200}{5}\right)^2$ | $= 5,33$ |
| $\phi_b M_{allow} = 0,9 \left[ C_1 \left(\frac{S}{D_o}\right) - C_2 \left(\frac{S}{D_o}\right)^2 - C_3 \right] M_e$ | $= 0,9 \left[ 8,17 \left(\frac{200}{5}\right) - 2,85 \left(\frac{200}{5}\right)^2 - 5,33 \right] 9056768$ |
| $= 4206370,61 \text{ N.mm}$ | $Gesa Vertikal Tee di Opening Pertama$ |
| Wide Flange Beam                                      | Cellular Beam                                      |
|------------------------------------------------------|---------------------------------------------------|
| Lokasi opening pertama                               | Geser                                             |
| \( x = e + 0.5D_0 = 100 + 0.5(200) = 200 \text{mm} \) | Geser Ultimit                                     |
| \( V_u = 57418,17 \text{N} \)                       |                                                   |
| \( V_{u\text{-top-tee}} = \frac{A_{t\text{-top-net}}}{A_{net}} V_u = \frac{1000}{2000} \cdot 57418,17 \) | \( A_{t\text{-bottom-net}} V_u = \frac{1000}{2000} \cdot 57418,17 \) |
| \( V_{u\text{-bottom-tee}} = \frac{A_{t\text{-bottom-net}}}{A_{net}} V_u = \frac{1000}{2000} \cdot 57418,17 \) | \( = 28709,09 \text{N} \) |
| Kuat Geser Nominal :                                  |                                                   |
| Persyaratan                                          |                                                   |
| \( \frac{h}{t_w} = \frac{d_{t\text{-top-net}}}{t_{w\text{-top}}} \leq 1,1 \sqrt{\frac{k_v}{F_y}} \) maha \( C_{v2} = \) | 1.0                                               |
| \( \frac{h}{t_w} = \frac{d_{t\text{-top-net}}}{t_{w\text{-top}}} = \frac{68.3}{5} = 13.66 \) |                                                   |
| \( 1,1 \sqrt{\frac{k_v}{F_y}} = 1,1 \sqrt{1,2 \times \frac{200000}{240}} = 34,8 \) |                                                   |
| \( \Phi_v V_{n\text{-tee-top}} = \Phi_v 0,6. F_y \cdot (d_{t\text{-top-net}} \cdot t_{w\text{-top}}). C_{v2} = 1 \times 0,6 \times 240 \times (68.3 \times 5) \times 1 \) | \( = 49176,9 \text{N} \) |
| Geser Vertikal Pada Bagian Kotor                      |                                                   |
| Geser                                               |                                                   |
| \( V_u = 57829,14 \text{N} \)                       |                                                   |

Gambar 12. Momen dan Geser Ultimit
**Wide Flange Beam**

**Cellular Beam**

Kuat Geser
Membuat asumsi fillet yang sama dengan ETABS untuk bagian kotor:

\[
h = \sqrt{\frac{2}{k_f \cdot c}} \quad \text{maka} \quad C_{v1}
\]

\[
h = d_g - (t_{f-tee-top} + r_{tee-top}) + (t_{f-tee-bot} + r_{tee-bot})
\]

\[
= 336.6 - (8 + 12) + (8 + 12)
\]

\[
= 296.6
\]

\[
\frac{h}{t_w} = \frac{296.6}{5} = 59.3
\]

1.1 \( \sqrt{\frac{k_f \cdot c}{F_y}} = 1.1 \sqrt{\frac{1.2 \times 20000}{240}} = 34.8
\]

\[
C_{v1} = \frac{1.1 \sqrt{k_f \cdot c}}{h/t_w} = \frac{34.8}{59.3} = 0.59
\]

\[
\varphi_{v_{n-gross}} = \varphi_{v} \times 0.6 \times (d_g \times t_w) \cdot C_{v1}
\]

\[
= 0.9 \times 0.6 \times 240 \times (336.6 \times 5) \times 0.59
\]

\[
= 127902.8 \text{ N}
\]

\[
\varphi_{Vn} > V_L = \text{OK}
\]

\[
W_{dead} = 0.002 \times L = 0.002 \times 6000 = 12 \text{ N/mm}^2
\]

\[
W_{live} = 0.005 \times L = 0.005 \times 6000 = 30 \text{ N/mm}^2
\]

Lendutan Beban Mati

\[
\delta_{dead} = \frac{W_{dead} \times L^4}{384 \times E \times (0.9 \times \text{Steel-net})}
\]

\[
= \frac{12}{12} \times \frac{384 \times 200000 \times (0.9 \times 1.05722 \times 10^{11})}{384 \times 200000 \times (0.9 \times 1.05722 \times 10^{11})}
\]

\[
= 0.11 \text{ mm}
\]

Lendutan Beban Hidup

\[
\delta_{live} = \frac{W_{live} \times L^4}{384 \times E \times (0.9 \times \text{Comp-net})}
\]

\[
= \frac{30}{12} \times \frac{384 \times 200000 \times (0.9 \times 191702230283235)}{384 \times 200000 \times (0.9 \times 191702230283235)}
\]

\[
= 0.00015 \text{ mm}
\]
Wide Flange Beam

Cellular Beam

\[ \delta_{\text{dead}} + \delta_{\text{dead}} = 0.11 + 0.00015 \]
\[ = 0.11015 \text{ mm} \leq \frac{L}{280} = 21.42 \text{ mm} \]
\[ \text{OK} \]

Further calculations on each cellular beam type can be seen in the appendix, while the size (type) of the beam used is as follows:

Table 7. List of Cellular Beam Size

| Nama Balok | Ukuran (mm) | Tinggi (mm) | Lebar (mm) | Lubang Cellular Ø | Spasing Ø |
|------------|-------------|-------------|------------|--------------------|-----------|
| A          | 250x125x5x8 | 334.6       | 124        | 200                | 300       |
| B          | 300x150x5.5x8 | 421.2      | 150        | 240                | 360       |
| C          | 350x175x6x9  | 471.2       | 175        | 280                | 420       |
| D          | 350x175x7x11 | 471.2       | 175        | 280                | 420       |
| E          | 346x174x6x9  | 467.2       | 174        | 280                | 420       |
| F          | 400x200x7x11 | 538         | 200        | 320                | 480       |
| G          | 400x200x8x13 | 538         | 200        | 320                | 480       |
| H          | 450x200x9x14 | 605.9       | 200        | 360                | 540       |
| I          | 500x200x10x16| 673.2       | 200        | 400                | 600       |
| J          | 600x200x11x17| 816.5       | 200        | 500                | 750       |
| K          | 600x300x12x20| 807         | 300        | 480                | 720       |

(Source: Author)

4. Conclusions & Suggestions

4.1. Conclusions

Based on the results of the research it can be concluded that:

Table 8. Beams Checked Against The Shear

| No | Steel Type      | \( \Omega V_u \) | \( \Omega V_n \) | Status |
|----|-----------------|------------------|------------------|--------|
| 1  | WF 400x200x8x13 | 57829,4          | 371174,4         | OK     |
| 2  | CB 250x125x5x8  | 57829,14         | 127902,85        | OK     |

Table 9. Beams Checked Against The Nominal Flexibility Strength

| No | Steel Type      | \( \Omega M_u \) | \( \Omega M_n \) | Status |
|----|-----------------|------------------|------------------|--------|
| 1  | WF 400x200x8x13 | 48410100         | 589650243,8      | OK     |
| 2  | CB 250x125x5x8  | 48410100         | 656930429,7      | OK     |

From the results of manual calculation verification, it shows that the cross section of WF 400x200x8x13 and CB 250x125x5x8 with a span length of 6 meters is declared strong and safe because it fill the necessary strong requirements, smaller than the strength of the plan.
From the graph above it can be seen the efficiency of using Cellular Beam compared to Wide Flange. Where the longer (m) use of Cellular Beam, will increases steel tonnage reduction.

From the graph above explains the percentage reduction of steel weight will continue to increase when the length of steel usage also increases. This concludes that the use of steel length with steel weight reduction will move linearly. Where in this project with a steel beam length of 1439.27m reduction of steel tonnage was at 19.5%.

4.2. Suggestions
Based on the results that have been researched can be given suggestions, including:
1. In calculating the analysis in this study using the standard burdens of existing regulations. To get a more accurate structural analysis, it is recommended to use the burdens that have been imposed on the structure design by the planner (consultant).
2. For further research, analysis of beams can use other types of blocks such as asymmetrical cellular or castellated. So that we will get a broader conclusion than other alternatives.

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Biographies

Donald Essen was a professor who, today, actively teaches at the Mercubuana University Jakarta with a concentrate on structure. He got a bachelor's degree in civil engineering from the Bandung Institute of Technology in 2002, a Master’s degree in engineering specialist from the Bandung Institute of Technology in 2007. He is a member of the Indonesian Society of Civil Engineers, registered as HAKI Professional Engineer, also Class A professional for construction engineering from Dinas Pengawasan dan Penertiban Bangunan DKI Jakarta (DPPB). Currently the director of ESK Enjiniring Company.

Muhammad Nur Rahman was born in Yogyakarta, a special region of Yogyakarta on August 9th, 1997. After graduation a vocational high school education in building engineering department continued his undergraduate civil engineering education at Mercubuana University Jakarta in 2016 to 2020 by compiling the final project is “Efficiency and effectiveness comparative analysis of wide flange beams and cellular beams in a case project united tractor”, also active as a staff in building construction project.