EFFECTS OF OUTRIGGER & BELT TRUSS SYSTEM ON HIGH-RISE BUILDING STRUCTURE PERFORMANCE

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Abstract. Using the lateral stiffener system, outrigger & belt truss is one of alternative to reduce the period of fundamental vibrate, displacement, and inter-story drift on high-rise building due to earthquake. The method that used to analysis structure performance, either it used an outrigger & belt truss system or not in post-elastic seismic load condition is nonlinear static analysis with pushover. The result of pushover analysis which shown the performance of building structure when an earthquake occurs, known as performance based design. This research use 4 models building (A-B-C-D) with 62 floors of tower and 6 floors of podium, has dual system portal combination with particular concrete shear-wall and located in the City of Jakarta which soft soil categorize. Building A doesn’t has outrigger & belt truss, meanwhile building B has it and the material of both buildings are reinforcement concrete structure. Building C doesn’t has outrigger & belt truss, meanwhile building D has it and the material of both buildings are profile steel structure. Seismic load design based on Source Map and Indonesian Earthquake Danger 2017 in analysis was determine as seismic repeat load which has possibility to become bigger during age of building structure (50 years), 2 %. Building A and B has Immediately Occupancy performance level, building C is Damage Control and building D has Immediately Occupancy performance.

1. Introduction
The construction of high-rise building has become an iconic for every country including DKI Jakarta and a regulation in planning must concern to safety and geographical of the region. Building a 62-story building requires much costs, an economic-safe structural system is needed, and one of them is a dual system using an additional lateral outrigger stiffener and belt truss. Placing a diagonal outrigger system and belt truss in different places on a 60-story building and the results can reduce the lateral deflection of the building, intersection between levels, and moments in core-wall area [1]. The combination of using an outrigger (connecting the perimeter-core-wall column) with a belt truss (connecting the perimeter columns) at the right floor position can control the lateral deflection of the building and the deviation between levels according to the target [2]. Using outrigger and belt truss systems with steel structure materials is more effective when compared to using concrete structures. All three journals did not explicitly mention the performance of high-rise building structures using outrigger & belt truss systems with reinforced concrete structures and profile steel structures [3]. Therefore, based on three statement above, furthermore research is needed to determine the performance of a high-rise building using reinforced concrete structure and steel structure profile materials if it uses an outrigger and belt truss systems. This study propose to conduct a comparative analysis of structure performance, either using outrigger and belt truss system or not. So that, the results can be a reference in using an outrigger and belt truss system in a 62-stories high-rise building.
2. Outrigger and Belt Truss System

Outrigger is a high beam connecting the core wall with an exterior column that is connected by a belt truss that functions as a virtual outrigger because the placement is not in the interior but still functions outrigger [8]. The working principle of the outrigger accepts the transfer of the bolt moment due to the lateral force to the horizontal coupling force of the core wall through the diaphragm plate. The horizontal coupling force is accepted by the belt truss and will convert the horizontal coupling force into a vertical coupling force in the exterior columns.

![Diagram of Outrigger & Belt Truss System Placement on the Building Structure](image)

Figure 1. Outrigger & Belt Truss System Placement on the Building Structure

Getting displacement target on the earthquake actual condition (performance based design) and structure performance level (immediately occupancy, damage control, and life safety level) obtained through pushover analysis based on the ATC-40 method [7] and FEMA-440 [11].

3. Method

The flow of research methodology begins with data collection, literature study, structure model of 62-stories structure using an outrigger & belt truss system or not (structural material; reinforced concrete and steel profiles), analysis free vibration and Respond dynamic use ETABS program [4][13] and base on regulation of SNI 1726 2012 [5] and ASCE standard 7-16 [6], evaluation of performance based design, actual value of parameter respons R, Ωo, Cd, and inference.

3.1 Design Criteria

The study uses four types of building model (A, B, C, D) with the same number of each floors, 62 floors and 6 podium floors. Building A (does not have an outrigger & belt truss systems) and Building B (has an outrigger & belt truss systems) 228 m from the lateral clamping level with reinforced concrete material. Building C (does not have an outrigger & belt truss system) and Building D (has an outrigger & belt truss system) 204 m from the lateral clamping level with profile steel material. Buildings A, B, C, D function as offices, based on SNI 1726-2012 [5] included in the risk category II with earthquake priority factor Ie = 1.0, and located in City of Jakarta with soft land category (class E site). The acceleration response curve of the spectra was obtained from The Source Map and Earthquake Hazard of 2017 in Indonesia by inputting the longitude and latitude site obtained parameter values $S_s = 0.698$ and $S_I = 0.304$, in units of g, see Figure 2.

![Accelerated Spectrum Response Curves for Research](image)

Figure 2. Accelerated Spectrum Response Curves for Research
The building stands on the seismic category (KDS) = D, so the structure system is chosen dual system, which is a combination of special moment bearing system (SRPMK) with shear wall. Seismic reduction factor; \( R = 7 \), strong factor still \( (\Omega_0) = 2.5 \) and deflection magnification factor \( (C_d) = 5.5 \). Building analysis of earthquake is carried out in the condition of structural elements in a cracked state, so that the effective inertia of the cross section is reduced; and the reduction factor of the inertia of the cross section is cracked; shear-wall and concrete column 0.7, concrete cross section T 0.35, and concrete plate 0.25. Inertial reduction factor for steel column cross section and steel beam is 0.8. The loading used in the analysis is gravity loads: DL weight of building itself, super imposed dead loads SIDL (ceiling, finishing floor, ME room), partition loads (1.50 KN / m²), and LL live loads. Free vibration analysis, mass source activated; Gravity loads (DL, SIDL, Partition) with 1.0 reduction, and live load: 2.4 KN/m² office, corridor: 4.79 KN/m², with 0.25 reduction.

3.2 Structural Modelling
The structure model of building A, B, C, D begins with input: list of material, geometry of structure elements, acceleration response curve of earthquake spectrum, design response spectrum, loading, mass source (effective seismic weight), reduction factor of inertial cross-section, and the level of lateral clamping on the ground floor. The geometry structure of Building A and Building B is different from Building C and Building D, let see the Figures 3 and 4.

![Figure 3. Podium & Tower Typical Layout Building A & B](image)

![Figure 4. Podium & Tower Typical Layout Building C & D](image)

3.3 Modal Response Spectrum Analysis Method (Free Vibration)
This method begins defining the design spectral acceleration parameters, response spectrum, effective seismic weight, and combined response parameter.

3.4 Dynamic Response Spectrum Analysis Method
This analysis method is a sustainable of the free vibration analysis, which is the definition of the design earthquake load \( (0.85V_{static}/V_{dynamic}) \) for element design, displacement checking, inter story drift, and dual systems for 25% earthquake force distribution on a single system frame.
3.5 Non Linear Static Analysis Method (Pushover)
1. Define the type and scale factor of the gravity load to be pushed (push). Dead load (DL + SIDL) is scaled 100% and live load 25%.
2. Determine the control points to monitor the magnitude of the displacement of the structure and compile a pushover curve that shows the relationship of the basic shear force to the displacement.
3. Determine the control points to limit the distribution of the structure and arrange a pushover curve that shows the relationship of the basic shear force to placement.
4. Make pushover curve of various lateral force distribution patterns equivalent to the distribution of the inertia force so that displacement is an expectation to occurring the same like the actual earthquake.

3.6 Evaluation of Structure Performance Level
ATC-40-1996 Method [7]; by default it is already built-in to the ETABS v9.7.4 program. with stages; determine the value of CA = 0.4 SMS and Cv = SM1, structural behavior type (Type B - the new building structure has a long respond period), damping parameters, capacity spectrum curves, and performance points.
FEMA Method 440-2005 [11]; by default it is already built-in to the ETABS v17.0.1 program. with stages; determine the value of SS and S1, class sites "E", Respond 8 seconds long period, damping parameters, capacity spectrum curves, and performance point points.

3.7 Determination of Actual Ductility Reduction Factors: R, Ωo, Cd
Draw the capacity curve from the pushover analysis results and then calculate the ideal value for the respondent modification factor calculated using the response modification formula R=Ve/Vd, superior strong factor system Ωo=Vy/Vd, and deflection amplification factors using formula Cd =δy/δd.

4. Results and Discussion

4.1 Visualization Structure Model on ETABS Programs

Figure 5. Visual Plan and Building Section A&B

Figure 6. Visual Plan and Building Section C&D @Etabs
### 4.2 Vibration Period Fundamental Building A, B, C, D

**Table 1. Period Fundamental Building A, B, C, D**

| Building | Vibration Period Fundamental | Movement Variety Pattern | Mass Participation | Outrigger & Belt Truss |
|----------|-----------------------------|-------------------------|--------------------|-----------------------|
| A        | M1: 7.14 second             | u_y, u_x                | >90%               | -                     |
| B        | M1: 6.79 second             | u_y, u_x                | >90%               | uses                 |
| C        | M1: 8.54 second             | u_y, u_x                | >90%               | -                     |
| D        | M1: 6.88 second             | u_y, u_x                | >90%               | uses                 |

### 4.3 Displacement and Inter-story Drift Building A, B, C, D

**Table 2. Displacement and Inter-story Drift Building A, B, C, D**

| Building | Displacement Roof (m) | Inter-story Drift Max (m) | Outrigger & Belt Truss |
|----------|-----------------------|---------------------------|-----------------------|
| A        | δ_y: 0.640<3.5        | Δ_y: 0.00083<0.069        | -                     |
| B        | δ_y: 0.628<3.5        | Δ_y: 0.00087<0.069        | uses                 |
| C        | δ_y: 0.618<3.2        | Δ_y: 0.00092<0.065        | -                     |
| D        | δ_y: 0.634<3.2        | Δ_y: 0.00101<0.065        | uses                 |

### 4.4 Dual System SRPMK Vs Concrete Shear-wall Building A, B, C, D

**Table 3. Distribution of Story Shear Force (Building B)**

| Story | Load | Belt Truss Force (KN) | Column Force (KN) | Beam-Outrigger Force (KN) | Pier Force (KN) | Story Force (KN) | Frame Percentage Min 25% |
|-------|------|-----------------------|-------------------|---------------------------|----------------|-----------------|-----------------------|
|       |      | Fx       | Fy | R | Fx | Fy | R1 | Fx | Fy | R1 | Fx | Fy | R3 | Fx | Fy | R1+R2+R3 |                |
| 62    | EX   | 142      | 41 | 148 | 330 | 279 | 432 | 362 | 716 | 803 | 260 | 2193 | 2208 | 3443 | 36%            |
| 61    | EX   | 676      | 51 | 678 | 1945 | 641 | 2048 | 460 | 265 | 531 | 328 | 2068 | 2093 | 4673 | 55%            |
| 60    | EX   | -        | -  | -  | 3096 | 597 | 3153 | 677 | 530 | 860 | 246 | 884 | 917 | 4931 | 81%            |
| 32    | EX   | 972      | 101 | 977 | 7957 | 2824 | 8443 | 1375 | 1782 | 2251 | 1570 | 5408 | 5632 | 16326 | 66%            |
| 31    | EX   | 1829     | 109 | 1832 | 9262 | 2898 | 9705 | 1059 | 213 | 1080 | 1575 | 5413 | 5637 | 16422 | 66%            |
| 30    | EX   | -        | -  | -  | 11401 | 2690 | 11714 | 1733 | 1694 | 2423 | 834 | 1520 | 1734 | 15871 | 89%            |

**Table 4. Distribution of Story Shear Force (Building D)**

| Story | Load | Belt Truss Force (KN) | Column Force (KN) | Beam-Outrigger Force (KN) | Pier Force (KN) | Story Force (KN) | Frame Percentage Min 25% |
|-------|------|-----------------------|-------------------|---------------------------|----------------|-----------------|-----------------------|
|       |      | Fx       | Fy | R | Fx | Fy | R1 | Fx | Fy | R1 | Fx | Fy | R3 | Fx | Fy | R1+R2+R3 |                |
| 62    | EX   | 76       | 7  | 77 | 461 | 269 | 534 | 888 | 142 | 899 | 601 | 4082 | 4126 | 5559 | 26%            |
| 61    | EX   | 356      | 7  | 356 | 1101 | 3091 | 3851 | 995 | 38 | 995 | 766 | 4165 | 4235 | 9081 | 53%            |
| 60    | EX   | -        | -  | -  | 621 | 3756 | 3807 | 1482 | 79 | 1484 | 643 | 2202 | 2294 | 7585 | 70%            |
| 32    | EX   | 368      | 11 | 368 | 5138 | 14306 | 15200 | 2302 | 149 | 2307 | 2121 | 6518 | 6854 | 24361 | 72%            |
| 31    | EX   | 654      | 12 | 655 | 5526 | 15917 | 16849 | 1603 | 27 | 1603 | 2102 | 6456 | 6790 | 25242 | 73%            |
| 30    | EX   | -        | -  | -  | 2312 | 11391 | 11623 | 2814 | 167 | 2819 | 1517 | 2651 | 3054 | 17497 | 83%            |
4.5 Output of Pushover Static Nonlinear Analysis

![Graph showing output of Pushover Static Nonlinear Analysis](image)

| Step | Monitored Displ | Base Force | A-B | B-C | C-D | D-E | >E | A-IO | IO-LS | LS-CP | >CP | Total Hinges |
|------|-----------------|------------|-----|-----|-----|-----|----|------|------|------|-----|--------------|
| 0    | 0               | 0          | 25065 | 0   | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 1    | 0.324756        | 22725.305  | 25017 | 48  | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 2    | 0.67968         | 43459.8478 | 21477 | 7567 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 3    | 0.969863        | 52185.9128 | 19851 | 3588 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 4    | 1.457404        | 64583.3579 | 17498 | 5214 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 5    | 1.952099        | 73028.5953 | 15150 | 7913 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 6    | 2.777153        | 83339.9187 | 10922 | 8143 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 7    | 3.350641        | 93011.8856 | 9678  | 8297 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 8    | 3.49998         | 94338.2789 | 16674 | 8391 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |
| 9    | 3.49998         | 94338.5122 | 16674 | 8391 | 0   | 0   | 25065 | 0    | 0    | 0   | 25065   |

Figure 7. Capacity Curve, Collapse Pattern, & Table Classification Level

The results of pushover analysis with ETABS for x, y Building A, B, C, D are obtained in the order of Building 11, 22, 8, 12 steps of the thrust load pattern given according to the structure that can be used to destroy and can be used in the Table according to Building A analysis. Every step increase in the thrust load pattern is given, the plasticization condition of the element will increase gradually until it collapses (step 1 zero CP element performance, there are 34 elements having CP 11 performance) so that it can be pictured in the graph of the force and displacement relation to the structure, let see to the Figure 7.

4.6 Result of Evaluation Structure Performance Level (Performance Based Design)

Performance of Building A, B, C, D, with spectrum capacity show on Figure 8, below.

![Graph showing spectrum capacity curve-performance point](image)
Table 5. Performance Point & Performance Level Building A,B,C,D

| Building | ATC-40 Method | FEMA 440 Method |
|----------|---------------|-----------------|
|          | Inter-story Performance | Inter-story Performance |
|          | Base Shear (V-KN) | Displacement (D-m) | Drift Actual (D/H) | Level | Base Shear (V-KN) | Displacement (D-m) | Drift Actual (D/H) | Level |
| A        | 57376          | 1.80            | 0.0079 | IO   | 59877          | 1.65            | 0.0072 | IO   |
| B        | 78987          | 1.69            | 0.0074 | IO   | 69991          | 1.58            | 0.0069 | IO   |
| C        | 52188          | 2.47            | 0.012  | DC   | 42519          | 2.07            | 0.0102 | DC   |
| D        | 83812          | 1.79            | 0.0087 | IO   | 57655          | 1.74            | 0.0085 | IO   |

Table 6. Comparison of Displacement & Inter-story Drift Value, Building A,B,C,D

| Building | Design Seismic | ATC-40 | FEMA 440 |
|----------|----------------|--------|----------|
|          | Displacement (m) | Inter-story Drift Max | Displacement Target (m) | Inter-story Drift Actual (m) | Target Displacement (m) | Inter-story Drift Actual |
| A        | 0.64<3.5        | 0.00083<0.069 | 1.80<3.5 | 0.0079<0.069 | 1.65<3.5 | 0.0072<0.069 |
| B        | 0.62<3.5        | 0.00087<0.069 | 1.69<3.5 | 0.0074<0.069 | 1.58<3.5 | 0.0069<0.069 |
| C        | 0.62<3.2        | 0.00092<0.065 | 2.47<3.2 | 0.12<0.065 | 1.94<3.2 | 0.0102<0.065 |
| D        | 0.63<3.2        | 0.00101<0.065 | 1.79<3.2 | 0.0087<0.065 | 1.74<3.2 | 0.0085<0.065 |

4.7 Actual Response Parameters Value R, $\Omega_0$, Cd

Table 7. Comparison Response Parameters Building A,B,C,D

| Response Parameters | Seismic Design (Dual System) | Pushover Analysis |
|---------------------|------------------------------|-------------------|
|                     | Building A | Building B | Building C | Building D |
| R                   | 7           | 6.20       | 6.21       | 6.74       | 6.75       |
| $\Omega_0$          | 2.5         | 2.29       | 2.46       | 2.23       | 2.35       |
| Cd                  | 5.5         | 5.32       | 5.45       | 5.26       | 5.61       |
5. Conclusion
1. The fundamental vibratory period of Building B and Building D is smaller than Building A and Building C, it means that Building A and Building C are less rigid because they do not use an outrigger and belt truss systems. so an enlarged structure dimension is needed to minimize the fundamental vibrational period so as not to exceed the limit 0.1 N.
2. Requirements of frame, receive 25% level shear force from the double system portal level shear force, all four buildings have been fulfilled, but the absorption of Building C and Building D in some floors is approaching and slightly below 25% so the portal strength is increased, while Building A and Building B absorption above 50%. This means that Building A and Building B (concrete material) portals absorb greater story shear forces than Building C and Building D (steel material).
3. Performance Level of Building A and B with ATC 40 & FEMA 440 methods are Immediately Occupancy, Building C has Damage Control performance, and Building D has Immediately Occupancy performance. This means that use of outrigger and belt truss systems does not affect Building Performance Level B because performance level is the same like Building A. However, for Building D use of the system affects the performance level building which is Building D's Performance Level is better than Building C so that in terms of evaluating performance level the use of outrigger and belt truss systems is more effectively used in building with the profile steel material.
4. With an outrigger and belt truss system, the Actual Building B displacement and inter-story drift are smaller than Building A with a percentage of 8% and Building D is smaller than Building C with a percentage of 20%. Actual displacement and inter-story drift of pushover analysis results for Building A, B, C, D is greater than the results of dynamic spectrum response analysis but still smaller than limit.
5. Respond parameter of the Actual R, Ωo, and Cd structures, the result of the pushover analysis carried out with the force approach have different values for Building A, B, C, D. This is caused by differences in the configuration of the structural system and material, but the value is close to the response parameters earthquake design.

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