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Effect of behavior factor on column design of reinforced concrete frame

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Abstract— Generally, Malaysian citizen are very fortunate because their country is situated relatively far away from active seismic fault zones. Hence, seismic consideration is not taken into account in Malaysian construction industry. However, after experiencing tremors from Sumatra Andaman and Philippines earthquakes which caused vibration on buildings, local authority start to consider about implementing seismic design for new buildings. Since have very limited experience in dealing with seismic design, there is some uncertainties among engineers about level of ductility and behavior factor, q to be used and their effect on cost of material. This paper investigated the difference of steel reinforcement when seismic provision is considered in reinforced concrete design of general office building. A total three regular moment resisting frame had been designed based on Eurocode 8 with various level of behavior factor, q for ductility class medium. From this study, it is observed that the level of behavior factor, q is strongly influencing the cost of steel reinforcement where the decrement of cost is in range of 22.1 to 42.5% lower compared to the highest one.

***Keywords*—seismic design, Eurocode 8, ductility, reinforced concrete, column**

I. Introduction

Current practice among engineers in Malaysia to design reinforced concrete (RC) structures is still by referring to BS 8110 [1] which not includes any seismic provision. This is reasonable because Malaysia is situated relatively far away from active seismic fault zone. Therefore, only gravitational load had been considered for low rise buildings. However, in the last 10 years, several tremors originating from Sumatra Andaman earthquakes had been felt in Malaysian Soil and induced vibration on buildings. Started by a large earthquake on December 2004, Nias 2005, until the latest one which just occurred on 2nd July 2013 in Aceh, Malaysian citizens start to worry about this hazard. Within the same period, seismic events originating from Bukit Tinggi, Pahang were reported to have been felt in various parts of the country [2]. Therefore, the Malaysian Public Work Department (JKR) suggested that it was worthwhile to consider seismic design input for new buildings. Since have very limited experiences in seismic design, the engineers faced a lot of uncertainties to implement it in Malaysia. In term of ductility, the ductility class low (DCL) or ductility class medium (DCM) may be recommended for Peninsular Malaysia [3].

In seismic design, engineers have to deal with a concept known of behavior factor, q. According to Eurocode 8 [4], it is a factor which used for design purposes to reduce the forces obtained from a linear analysis, in order to account for the nonlinear response of a structure. The same concept also exists in American code which known as force or strength reduction factor, R [5]. Both concepts are promoted so the structures are designed to behave inelastically due to tremors for economical reason [6]. The level of behavior factor, q to be used in design depends on the material, type of structures and class of ductility. For RC moment resisting frame structures with DCM, the level of behavior factor, q is lies in range of 1.5 to 4.5 [4]. However, over the past few years, there are several scientific evaluation and comment on the level of behavior factor, q proposed by the code. Borzi and Elnashai [7] had concluded that both European and American standards are too conservative where the ductility demand which corresponds to the behavior factor, q is higher than the ductility supply. It is also found that the strength reduction factor, R resulting from forward directivity ground motions is smaller than those from non-forward directivity ground motions [8]. When subjected to repeated earthquake, maximum storey ductility demand of low rise RC building depends on the level of behavior factor, q [9]. According to Pappin et. al, [10] using higher level of behavior factor, q resulting in lower seismic design forces but leads to ductile detailing.

This paper investigated the difference of steel reinforcement required in RC column design when seismic load is considered. A regular three storey RC frame for hospital use had been designed for DCM with various level of behavior factor, q. The comparison of flexural and shear reinforcement in column is presented.

II. Analysis Procedure

In this study, a 2 dimensional moment resisting frame of three storey RC building regular in plan and elevation had been used as model. The frame is designed for hospital use with typical storey height of 3.3 m and three equal bays of 5.0

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m as shown in Figure 1. This frame is modified from two storey RC model which had been used in previous work [11, 12]. The frame had been designed repeatedly with various level of behavior factor, q for DCM. Three different level of behavior factor, q had been used for design which is equal to 1.5, 3.0 and 4.5. As a result, a total three frames with different design had been produced for comparison. In term of material, the design process was performed based on concrete compressive strength, f_{cu} = 30 N/mm^2 and yield strength of steel, f_y = 500 N/mm^2. To maintain the dynamic characteristic of the frame, similar size of section for columns and beams had been used for all three frames. Therefore, the size of column is equal to 375 mm x 375 mm while the size of beam at two lower storeys is assigned as 300 mm x 600 mm. For top storey, smaller size of beam with 250 mm x 550 mm had been used. Based on modal analysis, the fundamental period of vibration, T_1 for all frames is equal to 0.50 second.

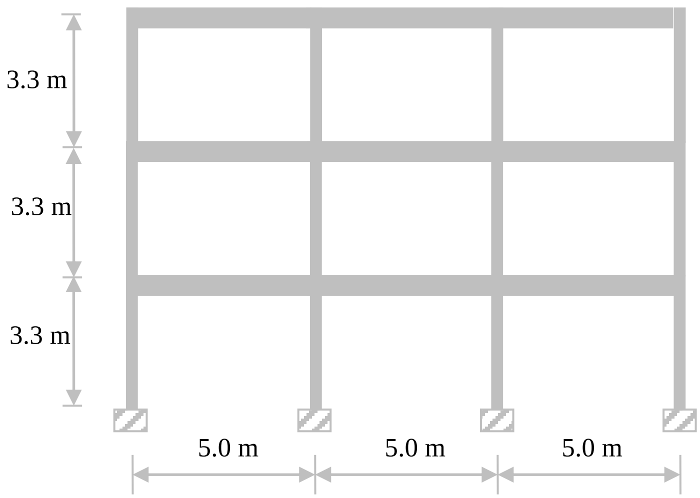

Figure 1: Elevation of three storey typical RC frame model

In order to get the magnitude of bending moment, shear force, and axial load for design of RC elements, the lateral force method analysis as proposed by Eurocode 8 [4] had been performed on each frame. In this method, the total earthquake action on building is represented by lateral load named as base shear force, F_b which had been determined using (1):

$$F_b = S_d(T_1) \cdot m \cdot \lambda \qquad (1)$$

where $S_d(T_1)$, m, and λ correspond to the ordinate of the design spectrum at period T_1, the total mass of the building above the foundation or above the top of a rigid basement, and the correction factor, respectively. Since the frame has more than two storey, the correction factor, λ is equal to 0.85 [4]. Then, the base shear force, F_b is proportionally distributed on each storey as lateral load using (2):

$$F_i = F_b \cdot \frac{s_i \cdot m_i}{\Sigma s_j \cdot m_j} \qquad (2)$$

where F_i is the horizontal force acting on storey i, m_i and m_j are the masses of storey i and j, respectively and s_i and s_j are the displacements of masses m_i and m_j, respectively in the fundamental mode shape.

The ordinate of the design spectrum at period T_1, $S_d(T_1)$ is determined by referring to the design response spectrum as shown in Figure 2. The Type 1 design response spectrum had been developed according to Eurocode 8 [4] which compatible with Soil D (v_s < 180 m/s). This is because buildings built on soft soil are occasionally subjected to tremors although Malaysia is situated on a stable part of the Eurasian plate [13]. The reference peak ground acceleration, a_{gR} used for development of design response spectrum is equal to 0.08g [2, 14] while the importance factor, γ_I is equal to 1.4 since the frame is designed for hospital and therefore classified in Class IV [4].

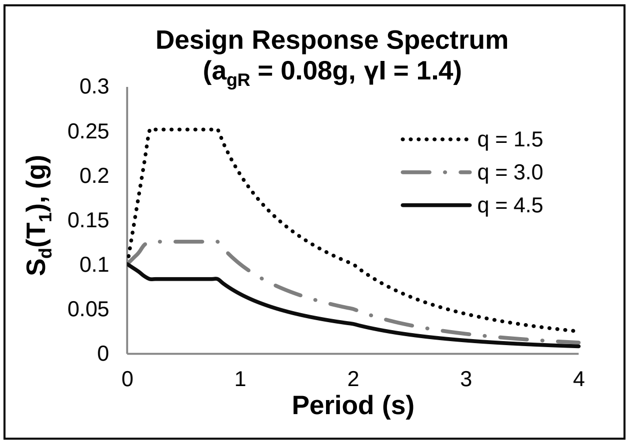

Figure 2: Design response spectrum for Type 1, Soil D

III. Result and discussion

In this study, all four frames had been subjected to similar gravitational load (dead load and live load) acting vertically on beam. But, due to different level of behavior factor, q used in developing the design response spectrum, different lateral load had been imposed on each frame. As a result, frame designed based on behavior factor, q equal to 1.5, 3.0, and 4.5 have total base shear force, F_b which are equal to 476kN, 238kN, and 162kN, respectively. As expected, higher level of behavior factor, q tends to decrease the magnitude of base shear force, F_b acting on frame. Therefore, bending moment, shear force, and axial load for frames with higher behavior factor, q should be lower and resulting in lighter reinforcement design.

When dealing with RC design, the designers have to play around with volume of concrete and amount of steel reinforcement. For example, small size of section resulting in low volume of concrete and high amount of steel reinforcement and vice versa. The designers also have to fulfill the requirement of minimum and maximum steel reinforcement as proposed by codes [1, 4]. Therefore, they have to select size of section, number and size of steel bar and adjust it smartly in order to fulfill the flexural demand from bending moment. For the same section, the designers also have to consider suitable arrangement of steel reinforcement to cater for shear demand. The global stiffness that developed the fundamental period of vibration, T_1 is strongly influenced by the size of section. Therefore, the latter is not altered as long as the amount of steel for column flexural reinforcement provided is not exceeds the limit of 4% of cross sectional area. It the limit is exceeded, the size of column has to be enlarged resulting in lower fundamental period of vibration, T_1 which cause the structure become stiffer and attracts higher inertia force.

For moment resisting frame system, RC column play an important role to support the beams and slabs then transfer the loads to the foundations [15]. Therefore, it is important for RC column to be designed and detailed adequately to resist both lateral and gravity loads. For DCM structures, column design is strongly related to the beam design where the magnitude of moment to be resisted by column, M_{Rc} is derived to be 1.3 times design moment of resistance of the beam, M_{Rb} [4, 16]. This concept is known as *Strong Column ~ Weak Beam* which is promoted to prevent the formation of plastic hinges in column. In this study, the design for exterior and interior column had been conducted separately due to different strength of beam at exterior and interior section. Figure 3 presents the comparison of total amount of flexural reinforcement for column to resist the derived bending moment.

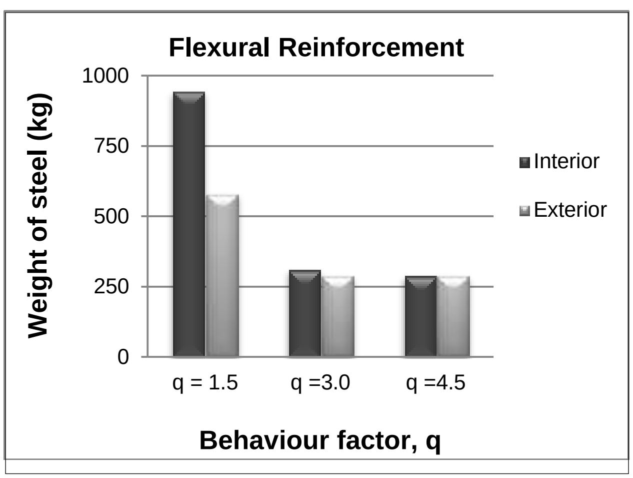

Figure 3: Effect of behavior factor, q on flexural reinforcement

In Figure 3, it is clearly observed that the amount of flexural reinforcement for both exterior and interior column decreases when the level of behavior factor, q is increases. This result is associated with the reduced lateral load for higher level of behavior factor, q. Lower bending moment obtained for beam design resulting in smaller amount of flexural reinforcement in beam which creates lower design moment of resistance of the beam, M_{Rb}. As explained in previous paragraph, the design of RC column in DCM structures is directly related to its beam design. Therefore, smaller amount of flexural reinforcement are required for columns of frames with higher level of behavior factor, q.

From Figure 3, it can be observed that for frame designed with behavior factor, q equal to 1.5, the amount of steel for flexural reinforcement is higher for interior column compared to the exterior one. This is due to higher design moment of resistance of the beam, M_{Rb} for interior section compared to the exterior. For frames designed with higher level of behavior factor, q the amount of steel reinforcement is similar for both interior and exterior column. The latter is associated with the requirement of minimum 1% of column cross sectional area must be provided in column with DCM design as proposed by the code [4]. This result indicates that as the level of behavior factor, $q \geq 3.0$, the area of steel required, As_{req} is very low due to lower design moment of resistance of the beam, M_{Rb}. Therefore, total area of steel provided, As_{prov} is at least 1% of cross sectional area of the column.

In RC design, shear or transverse reinforcement is important to resist shear forces and to avoid shear failure, to clamp together lap splices, to prevent buckling of longitudinal reinforcing bars, and to confine the concrete core to provide sufficient deformability (ductility) [15]. The comparison of total amount of steel used as shear reinforcement for interior and exterior column is shown in Figure 4. It is found that the amount of shear reinforcement is increases when the level of behavior factor, q is increases for both columns. This result is associated to the requirement of confinement reinforcement for column in DCM structures as proposed by Eurocode 8 [4].

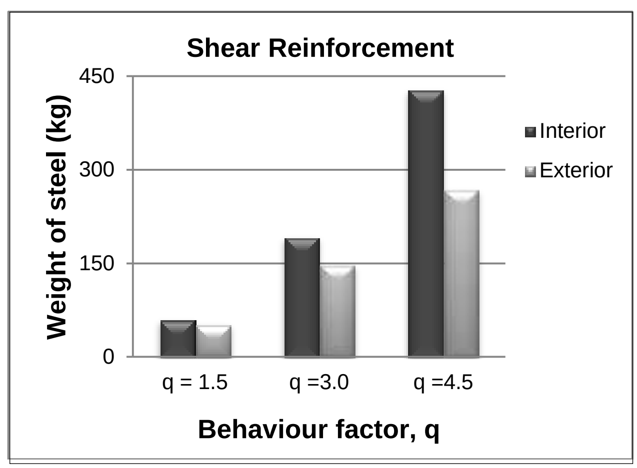

Figure 4: Effect of behavior factor, q on shear reinforcement

Among the main parameters which strongly influencing this confinement reinforcement is the gross cross-sectional width, b_c width of confined core,b_0 curvature ductility factor, μ_ϕ design value of tension steel strain at yield, $\varepsilon_{sy,d}$ and normalized design axial load, v_d [4]. Due to higher ductility demand, higher level of behavior factor, q tends to require higher mechanical volumetric ratio of confining hoops within the critical regions, $\omega_{\text{wd req}}$. In order to fulfill this requirement, the latter shall be sufficiently provided.

As explained in a design example by Elghazouli [17], the best solution for this matter is by decreasing the spacing of shear reinforcement, s which will automatically increase the provided mechanical volumetric ratio of confining hoops within the critical regions, $\omega_{\text{wd prov}}$. The latter also can be increased by using higher number and/or larger diameter of steel bar. Therefore, the amount of shear reinforcement in column is higher when higher level of behavior factor, q is considered. It is also presented in Figure 4 that the amount of shear reinforcement for interior column is higher compared to exterior column regardless the level of behavior factor, q. As explained, the requirement of confinement reinforcement also influenced by the normalized design axial load, v_d. Therefore, the interior column which located at middle part of the frame requires higher confinement reinforcement due to higher axial force, N compared to the exterior column.

Since all three frames have similar size of section for all corresponding elements, the total volume of concrete also becomes similar. Hence, the cost of steel used as flexural and shear reinforcement is strongly influencing the cost of material for all frames. Figure 5 depicts the total amount of steel reinforcement used in both interior and exterior column. It can be clearly observed that the highest amount of steel reinforcement is obtained for frame which used behavior factor, q equal to 1.5 in design. This is associated with high magnitude of base shear force, F_b acting on the frame resulting in high magnitude of bending moment, shear force, and axial load. Then, total amount of steel reinforcement is decreases due to lower amount of flexural reinforcement used for higher level of behavior factor, q as discussed in previous paragraph.

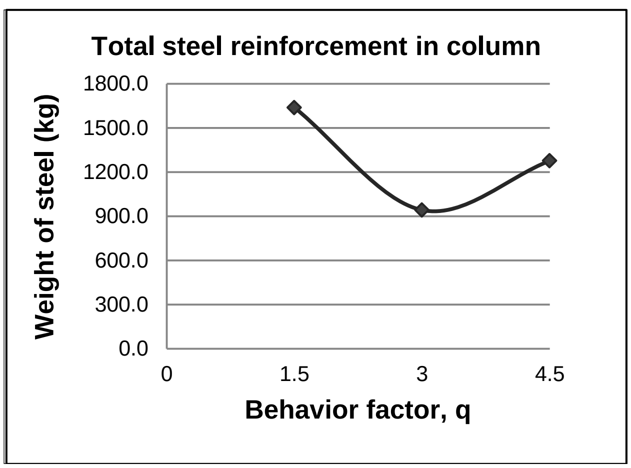

Figure 5: Effect of behavior factor, q on total steel reinforcement

However, as the behavior factor, q is greater than about 3.0; the total amount of steel reinforcement is increases. This is due to rapid increasing of total amount of shear reinforcement as the level of behavior factor, q is increases. For example, although have decrement in term of flexural reinforcement, frame designed with behavior factor, q equal to 4.5 have to use very high amount of shear reinforcement. As a result, the cost of steel for that frame becomes higher although subjected to smaller lateral load compared to frame designed with behavior factor, q equal to 3.0. Therefore, it can be concluded that in this study, the most economical design is obtained when using behavior factor, q equal to 3.0 where the cost of steel reinforcement can be saved up to 42.5% compared to the highest one.

IV. Conclusion

This study investigated the effect of behavior factor, q on seismic design of RC column. In this study, a three storey regular RC frame for hospital had been used as model. A total of three frames had been designed based on behavior factor, q equal to 1.5, 3.0, and 4.5 for ductility class medium. There are several conclusions can be drawn based on this study as follow:

- Total amount of steel provided as flexural reinforcement is decreases as the level of behavior factor, q is increases and vice versa. This is associated with the magnitude of base shear force, F_b which is strongly influenced by the level of behavior factor, q.
- Due to requirement of confinement reinforcement, total amount of steel provided as shear or transverse reinforcement is increases as the level of behavior factor, q is increases and vice versa.
- The sum of total flexural and shear reinforcement presents the total amount of steel reinforcement for design of RC column. It can be concluded that the level of behavior factor, q is strongly influencing the cost of steel reinforcement. Therefore, it is important to select the suitable behavior factor, q to obtained economic design without compromising safety.

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