CHAPTER 4

ANALYSIS OF EXPERIMENTAL RESULTS – CHANNEL SECTION

4.1 INTRODUCTION

Experimental observations made on the reinforced concrete thin-walled compression members tested are analysed in this chapter. The beneficial effect of vertical web stiffener is discussed through slenderness ratio. The effect of wall thickness is also discussed in this chapter employing height to flange width ratio. The parameters considered in the analysis to quantify the above effects are ultimate load, lateral deflection at mid height, strength ratio, stiffness and ductility factor. The strength degradation employed in the proposed empirical equation to predict the ultimate load is discussed in this chapter.

4.2 SLENDERNESS RATIO

Slenderness ratio ($\lambda$) is the ratio between height and minimum radius of gyration test specimens. The effect of slenderness ratio on the load bearing capacity, strength ratio, lateral deflection, stiffness, ductility factor and mode of failure of C$_{30}$ and C$_{0}$ specimens are considered in this portion. A series of graphs are drawn to illustrate and quantify the effect of slenderness ratio.

4.2.1 Ultimate Load

The variation of ultimate load ($P_{ue}$) with slenderness ratio ($\lambda$) of C$_{30}$ and C$_{0}$ series specimens is shown in Figure 4.1. The average decrease in load
bearing capacity of $C_{30}$ specimens with $\lambda$ less than 20 is quite rapid at 7.44kN per unit increase in $\lambda$. The same for $C_0$ specimens with $\lambda$ less than 20 is 3.29kN per unit increase in $\lambda$.

![Figure 4.1 Ultimate Load Capacity of $C_{30}$ and $C_0$ Specimens](image)

The above strength degradation for specimens with $\lambda$ ranging from 20 to 30 is 5.97kN and 2.78kN per unit increase in $\lambda$ for $C_{30}$ and $C_0$ series specimens respectively. The same is 4.75kN & 2.29kN and 3.54kN & 1.96kN per unit increase in $\lambda$ for $C_{30}$ and $C_0$ series specimens with $\lambda$ in the range of 30 to 40 and 40 to 50 respectively. For specimens with $\lambda$ greater than 50, the same is 2.39kN and 1.44kN per unit increase in $\lambda$. The above data indicate that for the band width of slenderness ratio considered, the successive difference in strength degradation is around 1.30kN and 0.50kN for $C_{30}$ and $C_0$ specimens respectively.

The rate of strength degradation in $C_{30}$ specimens in each band width of $\lambda$ considered is 2.26, 2.15, 2.07, 1.81 and 1.66 times more than that of $C_0$ specimens respectively. This is due to the enhanced stiffness infused by
vertical web stiffeners in C\textsubscript{30} specimens. The above rapid rate of strength degradation with increase in \( \lambda \) can also be interpreted as; the average increase in load capacity is 7.44\( kN \) per unit reduction in \( \lambda \) for C\textsubscript{30} specimens with \( \lambda \) less than 20. For the entire range of \( \lambda \) considered the weighted average increase in load capacity is 5.2\( kN \) per unit reduction in \( \lambda \) value. This value is in the proximity of strength degradation of specimens with \( \lambda \) ranging from 30 to 40. Hence it is reasonable to assume that, to derive maximum benefit of providing vertical web stiffener, the \( \lambda \) of the specimen shall be limited to 40. The above values also indicate the changes in the beneficial effect of vertical web stiffeners in different ranges of \( \lambda \). All the specimens tested were slender members with their \( \lambda \) value more than 12. All the specimens have also exhibited lateral deflection, cross sectional deformation and secondary moments, but the magnitude of the above parameters primarily depends on the value of \( \lambda \). The magnitude of beneficial effect of vertical web stiffener is also based on the mode of failure of the specimen, which in turn again depends on the value of \( \lambda \). Hence the magnitude of beneficial effect of vertical web stiffener changes from specimen to specimen. The above plot clearly indicates that over the entire range of \( \lambda \) considered, the effect of vertical web stiffener in enhancing the ultimate load is quite beneficial, but when \( \lambda \) exceeds 40, its magnitude goes on reducing in a significant manner.

The failure pattern of the specimens having \( \lambda \) greater than 45 indicates flexural failure (where the web laterally buckles and flanges move outward or inward globally corresponding to the displacement of web with very nominal amount of torsional deformation). For specimens having \( \lambda \) less than 35, the mode of failure has been flexural failure with large torsional deformation (where the entire cross section deforms angularly about the centre of rigidity of the specimen), called torsional flexural failure. For members having \( \lambda \) ranging from 35 to 45, the mode of failure varies from torsional flexure to flexural failure. The point of failure or initiation of first
crack is near the column head or near the column base for members with $\lambda < 35$, indicating torsional flexural failure. The same is near the mid height or away from the column head for members with $\lambda > 45$, indicating flexural failure. It is important to mention here that the most common local buckling mode of failure of thin-walled compression members was not exhibited by the specimens.

### 4.2.2 First Crack Load

The influence of slenderness ratio on first crack load ($P_{fc}$) is shown in Figure 4.2. As in the case of ultimate load, the web stiffener has significantly enhanced the first crack load of $C_{30}$ specimens over the entire range of $\lambda$ considered.

![Figure 4.2 Influence of Slenderness Ratio over First Crack Load](image)

The average first crack strength degradation for specimens with $\lambda$ less than 35 is 2.19kN and 1.40kN per unit increase in $\lambda$ for $C_{30}$ and $C_{0}$ series specimens respectively. The same is 1.87kN and 1.19kN for $C_{30}$ and $C_{0}$ series
specimens with $\lambda$ ranging from 35 to 45 respectively. For specimens with $\lambda$ greater than 45, the same is 1.60kN and 1.02kN per unit increase in $\lambda$. The above data indicates that the rate of above strength degradation of torsional flexural ($\lambda<35$) and flexural failure ($\lambda>45$) specimens is nominal as the flexural strength of the section influence the first crack load. The beneficial effect of vertical web stiffener is quite obvious from the above data, as the same increases the stiffness of $C_{30}$ specimens.

### 4.2.3 Strength Ratio

The dimensionless parameter called strength ratio, is defined as the ratio between strength of the section as found by experiment and theoretical strength of the section given by the product of cross sectional area and compressive strength of concrete. The ultimate strength ratio is given by the ratio between $P_{ue}$ and $(f_{cu}A)$ whereas the strength ratio at first crack is given by the ratio between $P_{fc}$ and $(f_{d}A)$. The influence of slenderness ratio on the strength ratio at ultimate and first crack load is shown in Figure 4.3. The strength ratio can be taken as a parameter which indicates the extent of torsional buckling or flexural buckling experienced by the specimen. Lower the value of strength ratio, higher is the buckling behaviour. The plot clearly indicates that the variation of strength ratio at ultimate and first crack load is proportional to each other as well as nearly linear for $C_0$ series specimens. The strength ratio at first crack load alone is nearly linear for $C_{30}$ specimens. The rate of degradation of strength ratio for $C_{30}$ series specimens at first and ultimate load is also identical to each other and remains at constant proportion for the entire range of $\lambda$ considered. The beneficial effects of vertical web stiffener at first crack and ultimate load gradually reduce and finally become zero with increase in the value of $\lambda$ within the range of $\lambda$ considered.
The variation of ultimate strength ratio with \( \lambda \) is an important parameter as it can be used as a measure to quantify the buckling characteristics of specimens. To quantify the above for \( C_{30} \) and \( C_0 \) series specimens, the strength ratio exhibited in two ranges of \( \lambda \) are considered. The average ultimate strength ratio degradation in \( C_{30} \) specimens with \( \lambda \) less than 40 is 0.0045 per unit increase in \( \lambda \) value. The same for specimens with \( \lambda \) more than 40 is 0.0019 per unit increase in \( \lambda \). The weighted average of the same for all the sixteen \( C_{30} \) specimens is 0.0037 per unit increase in \( \lambda \). The average ultimate strength ratio degradation in \( C_0 \) specimens with \( \lambda \) less than 40 is 0.0017 per unit increase in \( \lambda \) value. The same for specimens with \( \lambda \) more than 40 is 0.0014 per unit increase in \( \lambda \). The weighted average of the same for all the sixteen \( C_0 \) specimens is 0.0016 per unit increase in \( \lambda \). The above strength ratio degradation can be expressed in percentage as 1.014% and 0.65% of \( P_{ue} \) for \( C_{30} \) and \( C_0 \) specimens respectively. These values of strength ratio degradation are subsequently used in the formulation of empirical expressions for predicting ultimate axial load capacity of the test specimens. The modes of
failure of specimens are already classified in Section 4.2.1 based on $\lambda$ as torsional flexural failure ($\lambda < 35$) and flexural failure ($\lambda > 45$). The same can be further generalised based on strength ratio as torsional flexural failure occurs in specimens with $\lambda$ less than 40 and flexural failure in specimens with $\lambda > 40$, so that the undefined range of $\lambda$ starting from 35 to 45 is eliminated.

4.2.4 Lateral Deflection

The effect of slenderness ratio over lateral deflection of web at mid height ($\delta_{ue}$) is shown in Figure 4.4. The magnitude of lateral deflection of web at mid height of both web stiffened $C_{30}$ and un-stiffened $C_0$ series specimens at first crack load ($\delta_{fc}$) is nearly linear over the entire range of $\lambda$ considered. The lateral deflection exhibited by $C_{30}$ specimens at first crack load is more than that of $C_0$ specimens, as the first crack load of $C_{30}$ specimens is higher than that of $C_0$ specimens. The beneficial effect of web stiffener in specimens with $\lambda$ less than 40 gradually reduces as members become more slender and suffering nominal torsion. It can be inferred that nominal stiffening effect displayed by web stiffener at lower values of $\lambda$ is responsible for higher first crack loads of $C_{30}$ specimens. The beneficial effect of web stiffener at first crack load in flexural failure specimens with $\lambda$ greater than 40 (generalised in Section 4.2.3) remains constant. Both the specimens exhibited linear variation of first crack lateral deflection over the entire range of $\lambda$. In case of ultimate lateral deflection of web at mid height ($\delta_{ue}$), the effect of stiffener is well pronounced in the initial ranges of $\lambda$. The ultimate lateral deflection suffered by the $C_{30}$ specimens is significantly less even though they carried higher ultimate load for the entire range of $\lambda$. The reason for such a low value of lateral deflection is torsional flexural failure, which takes place near the supports and away from the mid height where the measurements were taken. The low magnitude of lateral deflection suffered by the $C_{30}$ series specimens
with $\lambda$ less than 40, reinforce the earlier failure mode classification; the dominant mode of failure in this range of $\lambda$ is torsional flexural failure.

**Figure 4.4 Variation of Lateral Deflection with Slenderness Ratio**

The average reduction in ultimate lateral deflection due to the provision of vertical web stiffener in C$_{30}$ series specimens with $\lambda$ less than 40 is found to be 34.20% less than that of C$_{0}$ specimens. While the same for C$_{30}$ specimen with $\lambda$ more than 40 is only 8.22%. The C$_{30}$ specimens with $\lambda$ less than 40 displayed much higher resistance to first crack by undergoing an average lateral deflection which is 28.29% more than that of C$_{0}$ specimens. While the same for C$_{30}$ specimen with $\lambda$ more than 40 is also higher at 18.28%. The C$_{30}$ series specimens are stiffer in the initial range of $\lambda$ and become less stiff as indicated above at higher ranges of $\lambda$. The beneficial effect of vertical web stiffener at ultimate stage can be effectively exploited by restricting $\lambda$ of specimens to 40 as it goes on reducing with increase in the slenderness of the member.
4.2.5  **Stiffness Factor**

The stiffness factor is defined here as the ratio between the applied load to the corresponding lateral deflection of web at mid height. The ratio between ultimate load and corresponding lateral deflection is termed as ultimate stiffness factor ($K_{ue}$) and that between first crack load and corresponding lateral deflection is initial stiffness ($K_{fc}$). The plot between slenderness ratio and ultimate and initial stiffness factors is shown in Figure 4.5.

![Figure 4.5 Variation of Stiffness Factor with Slenderness Ratio.](image_url)

The un-cracked stiffness or the initial stiffness of $C_{30}$ and $C_0$ specimens are nearly same for the specimens with $\lambda$ less than 25. The stiffening effect of web stiffener is nominally exhibited in a gradual manner with increase in $\lambda$, as loss of initial stiffness is more in $C_0$ specimens than in $C_{30}$ specimens. In case of ultimate stiffness factor, the rate of decay of stiffness in $C_{30}$ specimens is well pronounced in the initial range of $\lambda$. The loss of ultimate stiffness in specimens having $\lambda$ more than 40 is nominal when
compared with the earlier range of $\lambda$. The beneficial effect of vertical web stiffener can be quantified in the two ranges of $\lambda$ so far considered in other parameters. The average increase in ultimate stiffness factor due to the provision of vertical web stiffener in $C_{30}$ series specimens with $\lambda$ less than 40 found to be 152.54% of that of $C_0$ specimens. While the same for $C_{30}$ specimen with $\lambda$ more than 40 is only 37.30%. The average initial stiffness possessed by the un-cracked sections of $C_{30}$ specimens with $\lambda$ less than 40 is just 1.90% more than that of $C_0$ specimens. The same for $C_{30}$ specimen with $\lambda$ greater than 40 is 6.65%, stiffer than $C_0$ specimens. The significance of vertical stiffener at ultimate stage in resisting the torsional flexure can be illustrated with the following data. The average ultimate stiffness possessed by $C_{30}$ and $C_0$ specimens with $\lambda$ less than 40 is 102kN/mm and 38kN/mm respectively. The same for specimen with $\lambda$ more than 40 is 23kN/mm and 17kN/mm respectively. The insignificant contribution of vertical web stiffener towards first crack stiffness can be visualised by the findings given below. The initial stiffness possessed by $C_{30}$ and $C_0$ specimens with $\lambda$ less than 40 is 129kN/mm and 129kN/mm respectively. The same for specimen with $\lambda$ more than 40 is 92kN/mm and 88kN/mm respectively. These values indicate that the vertical web stiffener does not have any major role to play in an un-cracked specimen.

### 4.2.6 Ductility Factor

The ductility factor (DF) is defined as the ratio between ultimate lateral deflection of web at mid height ($\delta_{ue}$) and first crack lateral deflection of web at mid height ($\delta_{fc}$). The variation of same with the slenderness ratio is shown in Figure 4.6.
The ductility factor possessed by $C_{30}$ specimens are less than that of $C_0$ specimens for the entire range of $\lambda$ considered. The web stiffener provided makes the $C_{30}$ specimens stiffer than $C_0$ specimens, but at higher ranges of $\lambda$, the stiffening effect significantly reduced as members become more slender. The above plot also indicates that the $C_{30}$ specimens become more ductile without much compromise on stiffness, which means that $C_{30}$ specimens behave in a ductile manner without losing its strength and stiffness drastically. The average ductility factor of $C_{30}$ specimens with $\lambda$ smaller than 40 is 52.07% less than that of $C_0$ specimens. The same in $C_{30}$ specimens with $\lambda$ greater than 40 is 23.85% less than $C_0$ specimens, indicating that the ductility degradation is only around half of the initial value. It is important to note that the stiffness degradation in this range of $\lambda$ is about two third of its initial value as shown in section 4.2.5. The improvement in the ductility factor with increase in $\lambda$ can also be compared in terms of average ductility factors. The average ductility possessed by $C_{30}$ specimens with $\lambda$ smaller than 40 is 2.18, while the same is 4.53 for specimens with $\lambda$ greater than 40. The above values
for $C_0$ specimens are 4.46 and 5.96 respectively, indicating a gradual increase in ductility factor with $\lambda$.

### 4.2.7 Other Parameters

The influence and inter-relationship of other parameters such as first crack load, failure load, lateral deflection, stiffness and ductility factors are considered in this portion of the thesis.

#### 4.2.7.1 Load Vs Lateral Deflection

The variation of ultimate load ($P_{ue}$) with ultimate lateral deflection of web at mid height ($\delta_{ue}$) is shown in Figure 4.7. In case of members with $\delta_{ue}$ less than 3.00mm, there is no distinct difference between $C_{30}$ and $C_0$ series specimens. The extrapolated curve of $C_0$ specimens shows that, both the web stiffened and un-stiffened specimens would have behaved in a similar manner and carried the same ultimate load. But Figures 4.1 and 4.4 shows that this extrapolated portion of $C_0$ specimens is false and totally misleading.

![Figure 4.7 Variation of Ultimate Load with Ultimate Lateral Deflection](image)

Figure 4.7 Variation of Ultimate Load with Ultimate Lateral Deflection
This difference in the behaviour is mainly due to the effect of web stiffener in reducing lateral deflection and enhancing the load capacity. This can further be substantiated from Figure 4.4 that the vertical web stiffener is very effective in specimens with \( \lambda \) smaller than 40 leading to torsional-flexural failure. As the \( \lambda \) value increases further, there is a significant decrease in ultimate load capacity with corresponding increase in lateral deflection. The \( C_{30} \) specimens experienced nominally lower lateral deflection for a given load than that of \( C_0 \) specimens in this range due to the marginal effect of web stiffener.

4.2.7.2 Strength Ratio Vs Lateral Deflection

Figure 4.8 shows the plot between strength ratio and lateral deflection of web at mid height at ultimate stage. This plot also shows the range of variation of the above parameters in \( C_{30} \) and \( C_0 \) specimens.

![Figure 4.8 Variation of Ultimate Strength Ratio with Ultimate Lateral Deflection](image)
The ultimate strength ratio varies widely from 0.399 to 0.198kN/mm in C\textsubscript{30} specimens, but the same in C\textsubscript{0} specimens varies narrowly from 0.253 to 0.182kN/mm only. The ultimate lateral deflection at which failure occurred in C\textsubscript{30} specimens ranges from 5.94 to 1.43mm whereas the same in C\textsubscript{0} specimens is from 6.18 to 3.12mm. Above data indicates that C\textsubscript{0} specimens have a very narrow range of the above parameters due to which distinct difference either in strength ratio or lateral deflection among the groups of C\textsubscript{0} specimens is absent. In case of C\textsubscript{30} specimens, the range is wide enough to exhibit the above differences among the groups.

4.2.7.3 Stiffness Vs Lateral Deflection

The variation of ultimate stiffness (K\textsubscript{ue}) with ultimate lateral deflection (\(\delta\textsubscript{ue}\)) is shown in Figure 4.9. The ultimate stiffness possessed by C\textsubscript{30} series specimens at lower ranges of \(\lambda\) is more than that of C\textsubscript{0} specimens due to the provision of web stiffener.

![Figure 4.9 Variation of Ultimate Stiffness with Ultimate Lateral Deflection](image-url)
The same gradually reduces with increase in lateral deflection and at higher ranges of $\lambda$, it is nearly the same as that of $C_0$ specimens. This reduction is due to the flexural mode of failure of specimens in higher ranges of $\lambda$, where lateral deflection at mid height influences the failure and the stiffening effect of web stiffener is only marginal. The rate of reduction of stiffness in $C_{30}$ specimens is quite rapid with increase in lateral deflection in the initial stage, where specimens failed by torsional-flexural mode. In other words, the loss of stiffness in $C_{30}$ specimens in the initial ranges of $\lambda$ is high as members become more slender.

4.2.7.4 Stiffness Factor Vs Ductility Factor

The variation of ductility factor with the ultimate stiffness factor is shown in Figure 4.10. The ductility factor of $C_0$ specimens is more than that of $C_{30}$ specimens in the initial ranges of ultimate stiffness. This is mainly due to the web stiffener provided in $C_{30}$ specimens, which makes them stiffer than the $C_0$ specimens.

![Figure 4.10 Variation of Ductility Factor with Ultimate Stiffness](image.png)
The comparison of ductility factor and stiffness between two series of specimens is possible only up to 50kN/mm. Beyond which no such comparison can be made based on experimental data, as the maximum stiffness possessed by C₀ specimen is around 50kN/mm. If the curve of C₀ specimens is extrapolated, then in the higher ranges of ultimate stiffness, the plot shows higher ductility factor for C₃₀ specimens, which is also not true as un-stiffened C₀ specimens are ductile than C₃₀ specimens. The plot also shows the clustering of coordinates of C₀ specimens in the higher but narrow range of ductility factor. This indicates that distinct difference in ultimate stiffness among the groups of C₀ specimens is absent. In case of C₃₀ specimens, the range is wide enough to exhibit the above difference among the groups.

4.2.7.5 Strength Ratio Vs Stiffness

The variation of ultimate strength ratio with the ultimate stiffness is shown in Figure 4.11.
As predicted, the ultimate strength ratio of $C_{30}$ specimens is more than that of $C_0$ specimens for the entire range of stiffness considered. The average increase in strength ratio of $C_{30}$ specimens is also gradual than that of $C_0$ specimens. Due to the un-stiffened web of $C_0$ specimens, their coordinates get clustered at lower value of stiffness and strength ratio.

4.2.7.6 Ratio of Ultimate to First Crack Load

The variation of ratio of ultimate to first crack load ($P_{ue}/P_{fc}$) with slenderness ratio is shown in Figure 4.12.

![Figure 4.12 Variation of ($P_{ue}/P_{fc}$) Ratio with Slenderness Ratio](image)

The general profile of the curves is typically that of compression members. The $C_0$ specimens exhibit more consistent value for the above ratio than $C_{30}$ specimens. The ratio of ultimate load to first crack load rapidly decreases with increase in slenderness ratio for $C_{30}$ specimens than $C_0$ specimens due to the provision of web stiffener. The $C_{30}$ and $C_0$ specimens
with \( \lambda \) greater than 40 possess the \( P_{ue}/P_{fc} \) ratio in a consistent manner. The same in the range of torsional-flexural failure is quite erratic as many factors influence the failure such as location of point of failure, initiation of first crack etc. The plot also indicates that for \( C_{30} \) specimens in the higher range of slenderness ratio, the effect of vertical web stiffener completely vanishes and the failure takes place soon after the formation of first crack. On average \( C_{30} \) specimens’ ultimate failure load is 1.30 times that of first crack load. The same for \( C_0 \) specimens’ is 1.22 times its first crack load.

### 4.3 HEIGHT TO FLANGE WIDTH RATIO

The effect of height to flange width ratio (\( h/b_f \)) on the load bearing capacity, strength ratio, lateral deflection, stiffness factor, ductility factor and mode of failure of \( C_{30} \) and \( C_{25} \) specimens are considered in this portion. A series of graphs are drawn to illustrate and quantify the effect of wall thickness through height to flange width ratio. Experimental data of \( C_{25} \) series validation specimens are used here to quantify the effect of wall thickness in terms of height to flange width ratio.

#### 4.3.1 Strength Ratio

The influence of \( h/b_f \) ratio on the strength ratio is shown in Figure 4.13. The ultimate strength ratio (\( P_{ue}/F_{cu} \cdot A \)) of \( C_{30} \) specimens is more than that of \( C_{25} \) specimens in the initial ranges of \( h/b_f \) ratio. The same is gets reversed when \( h/b_f \) ratio goes beyond 12. Hence the \( h/b_f \) ratio of 12 can be taken up as an indicator point where the behaviour of specimen changes. The \( C_{30} \) specimens have 5mm additional wall thickness and 10mm additional web stiffener width. This makes them stiffer than \( C_{25} \) specimens and normally fails by torsional-flexural mode rather than flexural failure mode. The first crack strength ratio (\( P_{fc}/F_{d} \cdot A \)) also follows the same pattern. The first crack strength
ratio possessed by $C_{30}$ specimens is more than that of $C_{25}$ specimens as long as $h/b_f$ ratio is less than 11 and beyond which it gets reversed.

![Figure 4.13 Variation of Strength Ratio with h/b_f Ratio.](image)

Hence in both cases, the reversal of strength ratio takes place between specimens when $h/b_f$ ratio is around 12. It clear from the plot that stiffer specimens possess higher strength ratio as long as $h/b_f$ ratio is less than 12 and beyond 12, less stiffer specimens have the higher strength ratio. It can be concluded that $h/b_f$ ratio 12 can be taken as the bench mark point, which determines the mode of failure. Torsional-flexural failure is the mode of failure for specimens with $h/b_f$ ratio less than 12 and for the higher range of $h/b_f$ ratio, flexural mode of failure is the governing mode of failure.

On examining the effect of wall thickness, the following salient features can be highlighted. The $C_{30}$ specimens with $h/b_f$ ratio less than 12, on average possess 6.72% higher ultimate strength ratio than that of $C_{25}$ specimens. The same specimens with $h/b_f$ ratio greater than 12 have 1.64% lesser ultimate strength ratio than that of $C_{25}$ specimens. In case of strength
ratio at first crack, the $C_{30}$ specimens with $h/b_f$ ratio smaller than 12 possess 7.22% higher average strength ratio than $C_{25}$ specimens. The same is 6.43% lesser than that of $C_{25}$ specimens with $h/b_f$ range greater than 12. The entire sixteen $C_{30}$ specimens on average have 3.93% and 2.67% more strength ratio than $C_{25}$ specimens at ultimate and first crack load levels.

### 4.3.2 Load Capacity

The influence of $h/b_f$ ratio on the ultimate load ($P_{ue}$) and first crack load ($P_{fc}$) is shown in Figure 4.14. The ultimate load bearing capacity as well as first crack load of both the specimens reduces with increase in the $h/b_f$ ratio. The $C_{30}$ specimens have higher load capacity than $C_{25}$ specimens for the entire range of $h/b_f$ ratio considered due to higher wall thickness resulting in bigger cross sectional area. The effect of higher wall thickness of $C_{30}$ specimens is nearly uniform for the entire range, in case of ultimate load carrying capacity and slightly reducing with increase in $h/b_f$ ratio. Both the specimens behaved in a similar manner in shedding the load capacity beyond $h/b_f$ ratio of 12, as the members become more slender.

![Figure 4.14 Variation of Axial Load with h/b_f Ratio](image)
The effect of wall thickness can be seen in terms of increase in load capacity of the specimens. The C\textsubscript{30} specimens with h/b\textsubscript{f} ratio less than 12 carried on average 26.09\% higher ultimate load than the C\textsubscript{25} specimens. The same in the range of h/b\textsubscript{f} ratio greater than 12 is 29.74\%. For the entire range of h/b\textsubscript{f}, the C\textsubscript{30} specimens have carried 27.32\% higher ultimate load than that of C\textsubscript{25} specimens. The effect of wall thickness at first crack load is also nearly the same. It is 26.43\% and 23.39\% higher first crack load for C\textsubscript{30} specimens in the range of h/b\textsubscript{f} less than 12 and more than 12 respectively. On weighted average, the C\textsubscript{30} specimens carried 25.42\% higher first crack load than the C\textsubscript{25} specimens for the entire range of h/b\textsubscript{f} ratio.

4.3.3 Lateral Deflection

Figure 4.15 shows the variation of first crack (\(\delta_{fc}\)) and ultimate (\(\delta_{ue}\)) lateral deflection at mid height with the h/b\textsubscript{f} ratio.

![Figure 4.15 Variation of Lateral Deflection with h/b\textsubscript{f} Ratio](image_url)

The C\textsubscript{30} specimens suffered marginally less lateral deflection than that of C\textsubscript{25} specimens over the entire range of h/b\textsubscript{f} considered in the first crack
stage due to the higher stiffness possessed by them. As the h/b\(_f\) ratio increases both specimens nearly have the same intensity of lateral deflection. This decrease in stiffening effect is quite obvious beyond h/b\(_f\) ratio of 12 as shown by the plot. In case of ultimate lateral deflection, the C\(_{30}\) specimens suffered nominally less deflection in the initial ranges of h/b\(_f\) ratio up to 10, as torsional-flexural failure dominates the behaviour. Beyond this range, due to loss of stiffness and higher ultimate load, the C\(_{30}\) specimens have more lateral deflection than that of C\(_{25}\) specimens.

The effect of increase in wall thickness can be examined through the experimental observations. The C\(_{30}\) specimens with h/b\(_f\) ratio less than 12 undergone 3.01\% less ultimate deflection than C\(_{25}\) specimens, but beyond 12, the average deflection of C\(_{30}\) specimens is 13.69\% higher than that of C\(_{25}\) specimens. This indicates that the ductile behaviour is influenced by the width of the flange. More the flange width less will be the ductile behaviour on the part of both series of specimens.

4.3.4 Stiffness

The variation of stiffness at ultimate load (K\(_{ue}\)) and first crack load (K\(_{fc}\)) with h/b\(_f\) ratio is shown in Figure 4.16. The loss of stiffness with increase in h/b\(_f\) ratio is nominal as well as nearly gradual at first crack load for C\(_{25}\) series specimens, but the same is slightly rapid in C\(_{30}\) specimens due to larger dimensions of the web stiffener. The reduction in ultimate stiffness with increase in h/b\(_f\) ratio is quite rapid in both specimen series and it is well pronounced in C\(_{30}\) specimens. This rapid decay of stiffness in both series of specimens takes place up to h/b\(_f\) ratio of 8. Beyond 12, the loss of stiffness is very small and the behaviour of both series specimens is typically similar.
The effect of increase in wall thickness in enhancing the stiffness can be assessed through experimental data in addition to the plot shown above. The $C_{30}$ specimens with $h/b_f$ ratio less than 12 have on average 34.06% higher ultimate stiffness than the $C_{25}$ specimens. The same in the range of $h/b_f$ ratio greater than 12 is 14.08%. For the entire range of $h/b_f$, the $C_{30}$ specimens possessed 27.4% higher ultimate stiffness than that of $C_{25}$ specimens. The effect of wall thickness at first crack stiffness is also nearly the same. It is 41.33% and 24.49% higher first crack stiffness for $C_{30}$ specimens in the range of $h/b_f$ less than 12 and more than 12 respectively. On weighted average, the $C_{30}$ specimens carried 25.42% higher first crack load than the $C_{25}$ specimens for the entire range of $h/b_f$ ratio.

4.3.5 Ductility Factor

The variation of ductility factor ($\delta_{uc}/\delta_{fc}$) with $h/b_f$ ratio is shown in Figure 4.17. It is clearly shown in the plot that $C_{30}$ specimens have more
ductility factor than C_{25} specimens in the range of flexural buckling failure. In the range of torsional-flexural failure, the ductility factor possessed by C_{25} specimens is more than that of C_{30} specimens. This is due to the higher stiffening effect of vertical web stiffener in C_{30} series specimens. As h/b_f ratio increase, C_{30} specimen’s ductility factor becomes distinctly higher than C_{25} series due to higher flexural capacity possessed by it. This indicates that C_{25} specimens do not have large deflection capacity between first cracks to failure as exhibited by C_{30} series.

The influence of increase in wall thickness on ductility factor can be examined from the experimental observations. The C_{25} specimens with h/b_f ratio less than 12 have on average 9.62% more ductility factor than C_{30} specimens. The C_{30} specimens with h/b_f ratio more than 12 have on average 14.68% more ductility factor than C_{25} specimens.

![Figure 4.17 Variation of Ductility Factor with h/b_f Ratio](image)

*Figure 4.17 Variation of Ductility Factor with h/b_f Ratio*
4.3.6 Ratio of Ultimate to First Crack Load

The variation of ratio of ultimate to first crack load \( \frac{P_{ue}}{P_{fc}} \) with slenderness ratio is shown in Figure 4.18.

![Figure 4.18 Variation of \( \frac{P_{ue}}{P_{fc}} \) Ratio with Slenderness Ratio](image)

The general profile of the curves is typically that of compression members. The C\(_{25}\) specimens exhibit more consistent value for the above ratio than C\(_{30}\) specimens. The ultimate load to first crack load ratio rapidly decreases with increase in slenderness ratio for C\(_{25}\) specimens than C\(_{30}\) specimens due to lack of stiffness. The C\(_{30}\) specimens with \( \lambda \) greater than 40 possess the above ratio in a consistent manner. The same in the range of torsional-flexural failure is quite erratic as many factors influence the failure such as location of point of failure, initiation of first crack etc. The plot also indicates that for C\(_{25}\) specimens with higher range of slenderness ratio, failure takes place immediately after the formation of first crack. In case of C\(_{30}\) specimens with higher range of slenderness ratio, the same is not as abrupt as
C_{25} specimens and they sustain the load with a nominal increase before undergoing failure in flexural mode. On average, the first crack load of C_{30} specimens is 0.77 times its ultimate load. The same for C_{25} specimens is 0.82 times its ultimate load.