CHAPTER 5

ANALYSIS OF EXPERIMENTAL RESULTS – TRAPEZOIDAL SECTION

5.1 INTRODUCTION

Experimental observations made on the reinforced concrete thin-walled compression members made of trapezoidal section 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. Empirical equation to predict the ultimate load is suggested based strength degradation found from the experimental data.

5.2 SLENDERNESS RATIO

The effect of slenderness ratio on the load bearing capacity, strength ratio, lateral deflection, stiffness, ductility factor and mode of failure of \( T_{30} \) and \( T_0 \) specimens are considered in this portion. A series of graphs are drawn to illustrate and quantify the effect of slenderness ratio.

5.2.1 Ultimate Load

The variation of ultimate load (\( P_{ue} \)) with slenderness ratio (\( \lambda \)) of \( T_{30} \) and \( T_0 \) series specimens is shown in Figure 5.1. The average decrease in load
bearing capacity of T30 specimens with λ less than 20 is 12.53kN per unit increase in λ. The same for T0 specimens with λ less than 20 is quite rapid at 14.42kN per unit increase in λ.

The above strength degradation for specimens with λ ranging from 20 to 30 is 3.08kN and 6.73kN per unit increase in λ for T30 and T0 series specimens respectively. The same is 4.59kN per unit increase in λ for T30 specimens with λ in the range of 30 to 40. For T30 specimens with λ greater than 40, the same is 3.74kN per unit increase in λ. The strength degradation in T0 specimens with λ greater than 30 found to be 2.22kN per unit increase in λ.

![Figure 5.1 Variation of Ultimate Load with Slenderness Ratio](image)

**Figure 5.1 Variation of Ultimate Load with Slenderness Ratio**

The rate of strength degradation in T30 specimens in each band width of λ considered is 1.15, 2.19 and 1.68 times less than that of T0 specimens respectively. This is due to the geometrical shape of the trough section which is not so strong about both axes. The web stiffened T30
specimens get the benefit due to the enhanced stiffness infused by vertical web stiffeners. The above rapid rate of strength degradation with increase in $\lambda$ can also be interpreted as; the average increase in load capacity per unit reduction in $\lambda$ and the same is 12.53kN for $T_{30}$ specimens with $\lambda$ less than 20. For the entire range of $\lambda$ considered the weighted average increase in load capacity is 5.14kN per unit decrease 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 out of vertical web stiffener, the $\lambda$ of the specimen shall be limited to 40. The weighted average increase in load capacity for the entire range of $\lambda$ considered is 7.15kN per unit decrease in $\lambda$ value for $T_0$ specimens. 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.

The failure pattern of the specimens having $\lambda$ greater than 30 indicates flexural buckling mode of failure leading to formation of flexural cracks in the mid height regions of the specimen. For specimens having $\lambda$ less than 30, the mode of failure has been flexural buckling failure with large torsional deformation, forcing the entire cross section deforms angularly
about the centre of rigidity and leading to torsional-flexural buckling failure. Unlike the channel sections there is no transition range of failure, where the failure could be flexural buckling or torsional-flexural buckling. The point of failure or initiation of first crack is near the column head or near the column base for members with $\lambda < 30$ as in case of channel sections, indicating torsional-flexural buckling failure. The same is near the mid height or away from the column head for members with $\lambda > 30$, indicating flexural buckling 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 due to the non-homogeneous nature of concrete and global buckling behaviour.

5.2.2 First Crack Load

The influence of slenderness ratio on first crack load ($P_{fc}$) is shown in Figure 5.2. As in the case of ultimate load, the web stiffener has significantly enhanced the first crack load of $T_{30}$ specimens over the entire range of $\lambda$ considered. There is a marginal decrease in the beneficial effect of web stiffener with increase in $\lambda$. The average first crack strength degradation for specimens with $\lambda$ less than 30 is 8.04kN and 5.58kN per unit increase in $\lambda$ for $T_{30}$ and $T_0$ series specimens respectively. The same is 2.22kN and 1.95kN for $T_{30}$ and $T_0$ series specimens with $\lambda$ greater than 30 respectively. The above data indicates that the rate the strength degradation in torsional-flexural buckling range ($\lambda<30$) is significant and in the flexural buckling range ($\lambda>30$) it 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 $T_{30}$ specimens.
5.2.3 Strength Ratio

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 5.3. The strength ratio can be taken as a parameter which indicates the extent of torsional-flexural buckling or flexural buckling experienced by the specimens. 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 $T_0$ series specimens. The strength ratio at first crack load alone is nearly linear for $T_{30}$ specimens. The rate of degradation of strength ratio for $T_{30}$ series specimens at first crack and ultimate loads is identical to each other and remains at constant proportion for the entire range of $\lambda$ considered.
Figure 5.3 Influence of Slenderness Ratio over Strength Ratio

The beneficial effect of vertical web stiffener at first crack ($P_{fc}$) and ultimate load ($P_{ue}$) marginally decrease with increase in $\lambda$, but remains highly significant for both specimen series. To quantify the buckling characteristics of $T_{30}$ and $T_{0}$ series specimens, the strength ratio exhibited in two ranges of $\lambda$ are considered. The weighted average ultimate strength ratio degradation in $T_{30}$ specimens with $\lambda$ less than 30 is 0.0075 per unit increase in $\lambda$ value. The same for specimens with $\lambda$ more than 30 is 0.0040 per unit increase in $\lambda$. The average of the same for all the twelve $T_{30}$ specimens is 0.0057 per unit increase in $\lambda$. The weighted average ultimate strength ratio degradation in $T_{0}$ specimens with $\lambda$ less than 30 is 0.0055 per unit increase in $\lambda$ value. The same for specimens with $\lambda$ more than 30 is 0.0041 per unit increase in $\lambda$. The average of the same for all the twelve $T_{0}$ specimens is 0.0048 per unit increase in $\lambda$. The above strength ratio degradation can be expressed in percentage as 1.58% and 1.49% of $P_{ue}$ for $T_{30}$ and $T_{0}$ 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 5.2.1 as torsional-flexural buckling failure and flexural buckling failure based on slenderness ratio.

## 5.2.4 Lateral Deflection

The effect of slenderness ratio over first crack ($\delta_{fc}$) and ultimate load ($\delta_{ue}$) lateral deflection of web at mid height is shown in Figure 5.4. The magnitude of lateral deflection suffered by both web stiffened $T_{30}$ and un-stiffened $T_0$ series specimens at first crack load is nearly linear over the entire range of $\lambda$ considered. The lateral deflection exhibited by $T_{30}$ specimens at first crack load is more than that of $T_0$ specimens, as the first crack load of $T_{30}$ specimens is higher than that of $T_0$ specimens. The beneficial effect of web stiffener at first crack load in both series specimens reduces very marginally with increase in $\lambda$, even though the members become more slender and suffering nominal torsion. It can be inferred that nominal stiffening effect displayed by web stiffener is responsible for higher first crack loads of $T_{30}$ specimens. In case of ultimate lateral deflection of the web, the effect of stiffener is well pronounced in the flexural buckling failure ranges of $\lambda$. The ultimate lateral deflection suffered by the $T_{30}$ specimens is significantly less even though they carried higher ultimate load for the entire range of $\lambda$. The contribution of web stiffener in reducing lateral deflection in the initial ranges of $\lambda$ is as significant as in higher ranges of $\lambda$. The primary reason for the same is the failure mode (torsional-flexural buckling failure; $\lambda < 30$) experienced by the specimens. The second reason is low torsional strength due to the geometry of the section. The low magnitude of lateral deflection suffered by the $T_{30}$ series specimens with $\lambda$ less than 30, reinforce the earlier failure mode classification. In contrast to channel sections, web stiffened trapezoidal sections with low slenderness ratio suffer failure soon after the formation of first crack.
The average reduction in ultimate lateral deflection due to the provision of vertical web stiffener in T\textsubscript{30} series specimens with \( \lambda \) less than 30 found to be 36.72\% less than that of T\textsubscript{0} specimens. While the same for T\textsubscript{30} specimen with \( \lambda \) more than 30 is only 28.56\%. The T\textsubscript{30} specimens with \( \lambda \) less than 30 displayed much higher resistance to first crack by undergoing an average lateral deflection which is 19.66\% more than that of T\textsubscript{0} specimens. While the same for T\textsubscript{30} specimen with \( \lambda \) more than 30 is also higher at 23.22\%. The T\textsubscript{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 30 as it goes on reducing with increase in the slenderness of the member. T\textsubscript{30} specimens experienced 29.82\% less ultimate lateral deflection than that of T\textsubscript{0} specimens for the entire range of \( \lambda \) considered. The same specimens suffered 20.65\% more lateral deflection at first crack load than T\textsubscript{0} specimens for the entire range of \( \lambda \) considered.

Figure 5.4 Variation of Lateral Deflection with Slenderness Ratio
5.2.5 Stiffness Factor

The stiffness factor \((K)\) is defined here as the ratio between the applied load to the corresponding lateral deflection of web. The ratio between ultimate load and corresponding lateral deflection of web at mid height is termed as ultimate stiffness factor \((K_{ue})\) and that between first crack load and corresponding lateral deflection of web at mid height is initial stiffness \((K_{fc})\). The plot between slenderness ratio and ultimate and initial stiffness factors is shown in Figure 5.5.

The un-cracked stiffness or the initial stiffness of \(T_{30}\) and \(T_0\) specimens are nearly varying in a linear manner over the entire range of \(\lambda\) considered. The initial stiffness possessed by the \(T_{30}\) specimens is more than that of \(T_0\) specimens. The gain in initial stiffness due to the provision of web stiffener in \(T_{30}\) specimens is sustained over the entire range of \(\lambda\) considered. The effect of slenderness ratio on initial stiffness factor is very insignificant for the range of \(\lambda\) considered. In case of ultimate stiffness factor, the rate of decay of stiffness in \(T_{30}\) specimens is well pronounced in the initial range of \(\lambda\). The loss of ultimate stiffness in specimens having \(\lambda\) more than 30 is very 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 \(T_{30}\) series specimens with \(\lambda\) less than 30 found to be 96.24% of that of \(T_0\) specimens. While the same for \(T_{30}\) specimen with \(\lambda\) more than 30 is 85.41%. The average initial stiffness possessed by the un-cracked sections of \(T_{30}\) specimens with \(\lambda\) less than 30 is 14.35% more than that of \(T_0\) specimens. The same for \(T_{30}\) specimen with \(\lambda\) greater than 30 is 15.53% stiffer than \(T_0\) specimens.
The significance of vertical stiffener at ultimate stage in resisting the torsional-flexural buckling can be illustrated with the following data. The average ultimate stiffness possessed by $T_{30}$ and $T_0$ specimens with $\lambda$ less than 30 is 67.13kN/mm and 34.21kN/mm respectively. The same for specimen with $\lambda$ more than 30 is 24.42kN/mm and 13.17kN/mm respectively. The contribution of vertical web stiffener towards first crack stiffness can be visualised by the findings given below. The initial stiffness possessed by $T_{30}$ and $T_0$ specimens with $\lambda$ less than 30 is 77.74kN/mm and 67.99kN/mm respectively. The same for specimen with $\lambda$ more than 30 is 61.43kN/mm and 53.17kN/mm respectively. Above values indicate that the beneficial effect of vertical web stiffener is only marginal and it does not have any major role to play in an un-cracked specimen.

5.2.6 Ductility Factor

The ductility factor is defined as the ratio between ultimate and first crack lateral deflection of web at mid height. The variation of the same with the slenderness ratio is shown in Figure 5.6.
The ductility factor possessed by T\textsubscript{30} specimens is less than that of T\textsubscript{0} specimens for the entire range of \( \lambda \) considered. The web stiffener provided makes the T\textsubscript{30} specimens stiffer than T\textsubscript{0} specimens, but at higher ranges of \( \lambda \), the stiffening effect marginally reduced as members become more slender. The above plot also indicates that the T\textsubscript{30} specimens become more ductile without much compromise on stiffness, which means that T\textsubscript{30} specimens behave in a ductile manner without losing its strength and stiffness drastically at higher ranges of \( \lambda \) when compared with initial ranges of \( \lambda \). The ductility factor possessed by T\textsubscript{30} specimens at the initial ranges of \( \lambda \) is not good as in higher ranges as failure occurred soon after the formation of first crack. The average ductility factor of T\textsubscript{30} specimens with \( \lambda \) smaller than 30 is 99.60\% less than that of T\textsubscript{0} specimens. The same in T\textsubscript{30} specimens with \( \lambda \) greater than 30 is 71.79\% less than T\textsubscript{0} specimens, indicating that the ductility degradation is only around one fourth 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 5.2.5. 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 $T_{30}$ specimens with $\lambda$ smaller than 30 is 1.77, while the same is 3.13 for specimens with $\lambda$ greater than 30. The above values for $T_0$ specimens are 3.53 and 5.37 respectively, indicating a gradual increase in ductility factor with $\lambda$.

5.2.7 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.

5.2.7.1 Load Vs Lateral Deflection

The variation of ultimate load with ultimate lateral deflection is shown in Figure 5.7. In case of stiff members with low value of $\lambda$, the $T_{30}$ specimens carry higher load for a given deflection due to the presence of web stiffener. There is no distinct difference between $T_{30}$ and $T_0$ series specimens in terms of lateral deflection in the load range of 190kN to 220kN. Like wise, in case of slender members with higher value of $\lambda$, the $T_{30}$ specimens suffer lower lateral deflection for a given load than $T_0$ specimens due to the presence of web stiffener. This difference in the behaviour of $T_{30}$ specimens within the given range of $\lambda$ is mainly due to the effect of web stiffener in reducing lateral deflection at higher ranges of $\lambda$ and enhancing the load capacity in the lower ranges of $\lambda$. This can further be substantiated that the vertical web stiffener is very effective in enhancing the load bearing capacity of specimens with $\lambda$ smaller than 30 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 $T_{30}$ specimens experienced nominally lower lateral deflection for a given load than that of $T_0$ specimens in the higher ranges of $\lambda$ due to the marginal flexural stiffening effect of web stiffener.

5.2.7.2 Strength Ratio Vs Lateral Deflection

Figure 5.8 shows the plot between strength ratio and lateral deflection at ultimate stage. The ultimate strength ratio reduces more rapidly as members become more slender and suffering higher lateral deflection. In the initial ranges of $\lambda$, the $T_{30}$ specimens possess higher values of strength ratio than that of $T_0$ specimens. The above higher value of strength ratio is due the web stiffener and failure mode of the specimens. In this range of strength ratio, the type of failure is torsional flexure, where the $T_{30}$ specimens failed soon after the formation of first crack. In the lower ranges of strength
ratio, the $T_0$ specimens experienced more lateral deflection than $T_{30}$ specimens for a given value of strength ratio. This is also due to the presence of web stiffener, which arrests the lateral deflection of web.

![Variation of Ultimate Strength Ratio with Ultimate Lateral Deflection](image.png)

**Figure 5.8** Variation of Ultimate Strength Ratio with Ultimate Lateral Deflection

### 5.2.7.3 Stiffness Vs Lateral Deflection

The variation of ultimate stiffness with ultimate lateral deflection is shown in Figure 5.9. The ultimate stiffness possessed by $T_{30}$ series specimens at lower ranges of $\lambda$, where the ultimate lateral deflection is also low, is more than that of $T_0$ specimens due to the provision of web stiffener. The same gradually reduces with increase in lateral deflection and at higher ranges of $\lambda$, it is marginally lower than that of $T_0$ specimens. This reduction is due to the flexural buckling 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 $T_{30}$
specimens is quite rapid with increase in lateral deflection in the initial stage, where specimens failed by torsional-flexural buckling mode. In other words, the loss of stiffness in $T_{30}$ specimens in the initial ranges of $\lambda$ is high as members tend to become more slender and susceptible to large lateral deflections.

![Figure 5.9 Variation of Ultimate Stiffness with Ultimate Lateral Deflection](image)

**Figure 5.9 Variation of Ultimate Stiffness with Ultimate Lateral Deflection**

**5.2.7.4 Stiffness Vs Ductility Factor**

The variation of ductility factor with the ultimate stiffness is shown in Figure 5.10. The ductility factor of $T_0$ specimens is more than that of $T_{30}$ specimens in the initial ranges of ultimate stiffness. This is mainly due to the web stiffener provided in $T_{30}$ specimens that makes them stiffer than the $T_0$ specimens.
The comparison of ductility factor and stiffness between two series of specimens is possible only up to 60kN/mm. Beyond which no such comparison can be made based on experimental data, as the maximum stiffness possessed by T₀ specimen is around 60kN/mm. If the curve of T₀ specimens is extrapolated, then in the higher ranges of ultimate stiffness, the plot shows higher ductility factor for T₃₀ specimens, which is misleading and not true as un-stiffened T₀ specimens are more ductile than T₃₀ specimens as evident from Figures 5.5 and 5.6.

5.2.7.5 Strength Ratio Vs Stiffness

The variation of ultimate strength ratio with the ultimate stiffness is shown in Figure 5.11. As predicted, the ultimate strength ratio of T₃₀ specimens is more than that of T₀ specimens for the entire range of flexural failure as the web stiffener enhances the ductility factor without compromising on flexural stiffness as discussed in section 5.2.6. The average increase in strength ratio of T₃₀ specimens is also gradual than that of T₀.
specimens. Due to the un-stiffened web of $T_0$ specimens, their coordinates get clustered at lower value of stiffness and strength ratio.

![Graph](image)

**Figure 5.11 Variation of Ultimate Strength Ratio with Ultimate Stiffness**

### 5.2.7.6 Ratio of Ultimate to First Crack Load

The variation of ratio of ultimate load to first crack load with slenderness ratio is shown in Figure 5.12. The general profile of the curves is typically that of compression members. The ultimate load to first crack load ratio rapidly decreases with increase in slenderness ratio for $T_{30}$ and $T_0$ specimens in a similar manner. The $T_{30}$ and $T_0$ specimens with $\lambda$ greater than 30 possess the above ratio in a consistent manner. The same in the range of torsional-flexural buckling failure is quite erratic as many factors influence the failure such as location of failure zone, initiation of first crack etc. The plot also indicates that the $T_{30}$ specimens over the entire range of $\lambda$ considered possess lower value of ($P_{uc}/P_{fc}$) ratio due to lack of ductility, which forces the specimens to fail soon after the formation of first crack. In the higher range
of slenderness ratio, the effect of vertical web stiffener found to contribute more evenly with respect to $T_0$ specimens. On average, the ultimate failure load of $T_{30}$ specimens is 1.32 times that of first crack load. The same for $T_0$ specimens is 1.42 times its first crack load. These values indicate that $T_{30}$ specimens are stiffer at the same time nominally less ductile than $T_0$ specimens for the entire range of slenderness ratio considered.

Figure 5.12 Variation of $(P_{ue}/P_{fc})$ Ratio with Slenderness Ratio