CHAPTER FOUR
4.1 EXPERIMENTAL RESULTS AND DISCUSSIONS

There were two specimens for each grade of steel and two loading capacities for these various grades of steel. The specimens were tested under the same constant load capacity as tabulated below:

Table 4.1

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Cyclic Load 1</th>
<th>Cyclic Load 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>300W</td>
<td>0.50P = 122 KN</td>
<td>0.75P = 184 KN</td>
</tr>
<tr>
<td>350W</td>
<td>0.50P = 122 KN</td>
<td>0.75P = 184 KN</td>
</tr>
<tr>
<td>460W</td>
<td>0.50P = 122 KN</td>
<td>0.75P = 184 KN</td>
</tr>
</tbody>
</table>

4.1.1 Grade 300W @ 0.50P
Specimen 1 of Grade 300W was loaded with 122 KN at the midspan until failure.

Moment determination:
P = 122 KN

\[ R_a = \frac{P}{2} = \frac{122\text{KN}}{2} = 61\text{KN} \]

Maximum moment (moment @ midpoint), \( M_{300} = 61\text{KN}\times1.25\text{m} = 76.25\text{KNm} \)

Stress determination:
Considering the section at midspan directly under the point of loading where maximum stresses will be induced, as shown below.
\[ \sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I} \cdot c \]

Where:

- \( \sigma_{\text{midspan}} \) = maximum stress at midspan
- \( M_{\text{midspan}} \) = Applied bending moment at midspan
- \( C \) = Distance from neutral axis to surface of the specimen
- \( I \) = Cross-sectional moment of inertia

\[ \bar{y} = \frac{\sum A y}{\sum A} \]

- \( A_1 = 100 \times 16 = 1600 \text{mm}^2 \)
- \( A_2 = 16 \times 218 = 3488 \text{mm}^2 \)
- \( A_3 = 100 \times 16 = 1600 \text{mm}^2 \)

\[ \sum A = A_1 + A_2 + A_3 = 6688 \text{mm}^2 \]

- \( y_1 = 250 - 8 = 242 \text{mm} \)
- \( y_2 = \frac{218}{2} + 16 = 125 \text{mm} \)
- \( y_3 = \frac{16}{2} = 8 \text{mm} \)

- \( A_1 y_1 = 1600 \text{mm}^2 \times 242 \text{mm} = 387200 \text{mm}^3 \)
- \( A_2 y_2 = 3488 \text{mm}^2 \times 125 \text{mm} = 436000 \text{mm}^3 \)
- \( A_3 y_3 = 1600 \text{mm}^2 \times 8 \text{mm} = 12800 \text{mm}^3 \)

\[ \sum Ay = A_1 y_1 + A_2 y_2 + A_3 y_3 = 836000 \text{mm}^3 \]
\[ \overline{y} = \frac{\sum A y}{\sum A} = \frac{836000 \text{mm}^3}{6688 \text{mm}^2} = 125 \text{mm} \]

\[ I_1 = \frac{b_1 d_1^3}{12} + A_1 (y_1 - \overline{y})^2 \]
\[ = \frac{100 \text{mmx16}^3 \text{mm}^3}{12} + 1600 \text{mm}^2 (242 \text{mm} - 125 \text{mm})^2 \]
\[ I_1 = 21936533.33 \text{mm}^4 \]

\[ I_2 = \frac{b_2 d_2^3}{12} + A_2 (y_2 - \overline{y})^2 \]
\[ = \frac{16 \text{mm} x 218^3 \text{mm}^3}{12} + 1600 \text{mm}^2 (125 \text{mm} - 125 \text{mm})^2 \]
\[ I_2 = 13813642.62 \text{mm}^4 \]

\[ I_3 = \frac{b_3 d_3^3}{12} + A_3 (y_3 - \overline{y})^2 \]
\[ = \frac{100 \text{mmx16}^3 \text{mm}^3}{12} + 1600 \text{mm}^2 (125 \text{mm} - 8 \text{mm})^2 \]
\[ I_3 = 21936533.33 \text{mm}^4 \]

\[ \therefore I = I_1 + I_2 + I_3 = 57686709.33 \text{mm}^4 \]

\[ M_{\text{midspan}} = 76.25 \times 10^6 \text{ Nmm} \]

\[ c = 125 \text{mm} \]

\[ \therefore \sigma_{\text{midspan}} = \sigma_{\text{max}} = \frac{76.25 \times 10^6 \text{ Nmmx125mm}}{57.69 \times 10^6 \text{ mm}^4} = 165 \text{ N/mm}^2 \]

For minimum stress applied at midspan with P = 10 KN:

Minimum moment @ midspan, \( M_{\text{min}} = 5 \text{KNx1.25m} = 6.25 \text{KNm} \)

\[ \sigma_{\text{min}} = \frac{6.25 \times 10^6 \text{ Nmmx125mm}}{57.69 \times 10^6 \text{ mm}^4} = 13.5 \text{ N/mm}^2 \]

\[ \therefore \]

\[ \sigma_{\text{max}} = 165 \text{ N/mm}^2 \]

\[ \sigma_{\text{min}} = 13.5 \text{ N/mm}^2 \]

Stress Range, \( \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 151.5 \text{ N/mm}^2 \)

Mean Stress, \( \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{178.5}{2} = 89.25 \text{ N/mm}^2 \)
\[ \text{Stress Amplitude, } \sigma_a = \frac{\Delta \sigma}{2} = 75.75 \text{ N/mm}^2 \]

Strain gauge results

The strain values obtained during the experiment is shown below. The strain values were measured after every 100,000 cycles at a frequency of 1 Hz. 1 strain gauge was affixed at the top flange towards the support of the specimen while three strain gauges namely B, C and D were placed on the web within the zone of loading.

Table 4.2 – Strain gauge results

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Top Flange (microstrain)</th>
<th>Web - B (microstrain)</th>
<th>Web - C (microstrain)</th>
<th>Web - D (microstrain)</th>
<th>Stress MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17380</td>
<td>14705</td>
<td>16400</td>
<td>18105</td>
<td>165</td>
</tr>
<tr>
<td>100000</td>
<td>16865</td>
<td>14830</td>
<td>16620</td>
<td>18365</td>
<td>165</td>
</tr>
<tr>
<td>200000</td>
<td>16980</td>
<td>14800</td>
<td>16660</td>
<td>18390</td>
<td>165</td>
</tr>
<tr>
<td>300000</td>
<td>16875</td>
<td>14780</td>
<td>16660</td>
<td>18370</td>
<td>165</td>
</tr>
<tr>
<td>400000</td>
<td>16855</td>
<td>14840</td>
<td>16630</td>
<td>18390</td>
<td>165</td>
</tr>
<tr>
<td>500000</td>
<td>16860</td>
<td>14840</td>
<td>16670</td>
<td>18395</td>
<td>165</td>
</tr>
<tr>
<td>600000</td>
<td>16860</td>
<td>14810</td>
<td>16665</td>
<td>18380</td>
<td>165</td>
</tr>
<tr>
<td>700000</td>
<td>16840</td>
<td>14850</td>
<td>16660</td>
<td>18410</td>
<td>165</td>
</tr>
<tr>
<td>800000</td>
<td>16865</td>
<td>14840</td>
<td>16645</td>
<td>18410</td>
<td>165</td>
</tr>
<tr>
<td>900000</td>
<td>16870</td>
<td>14835</td>
<td>16650</td>
<td>18390</td>
<td>165</td>
</tr>
<tr>
<td>1000000</td>
<td>16850</td>
<td>14830</td>
<td>16670</td>
<td>18395</td>
<td>165</td>
</tr>
<tr>
<td>1100000</td>
<td>16860</td>
<td>14850</td>
<td>16675</td>
<td>18395</td>
<td>165</td>
</tr>
<tr>
<td>At failure -</td>
<td>16750</td>
<td>14930</td>
<td>16720</td>
<td>18500</td>
<td>165</td>
</tr>
<tr>
<td>1200000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until failure; the stress-strain curve yielded a straight line as shown below:
Relationship between Strain and cycles to failure

The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at every 100,000 cycles of loading.

**Top flange**

**Figure 4.2 – Top flange**
As can be seen from the figure above, there was a sharp contraction after the first 100,000 cycles and afterwards stabilization. This shows that the top flange was under compression.

**Web - B**

![Graph](Web - B of 300W @ 122KN cyclic loading)

**Figure 4.3 – Web B**

Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension. Two other strain gauges were placed on the web and these yielded similar result as shown in figures 4.4 and 4.5 below.

**Web - C**

![Graph](Web - C of 300W @ 122KN cyclic loading)

**Figure 4.4 – Web C**
Figure 4.5 – Web D

**Failure Cycle, time and shape:**

The beam failed by out-of-plane global buckling (figure 4.6a) at 1,200,000 cycles, which was approximately 333 hours of testing. The beam also showed a sign of in-plane local buckling at both the supports (figure 4.6b) and the point of loading (figure 4.6c).

Figure 4.6a – Specimen at failure (out-of-plane global buckling)
4.1.2 Grade 350W @ 0.50P

Specimen 2 of Grade 350W was loaded with 122 KN at the midspan until failure.
Moment determination:

\[ P = 122 \text{ KN} \]

\[ R_{\text{A}} = \frac{P}{2} = \frac{122 \text{ KN}}{2} = 61 \text{ KN} \]

Maximum moment (moment @ midpoint), \( M_{350} = 61 \text{ KNx1.25m} = 76.25 \text{ KNm} \)

Stress determination:

Considering the section at midspan directly under the point of loading where maximum stresses will be induced, as shown below.

\[ \sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I} \cdot C \]

Where:

\( \sigma_{\text{midspan}} \) = maximum stress at midspan

\( M_{\text{midspan}} \) = Applied bending moment at midspan

C = Distance from neutral axis to surface of the specimen
\[ I = \text{Cross-sectional moment of inertia} \]

\[ \bar{y} = \frac{\sum A_y}{\sum A} \]

\[ A_1 = 100 \times 16 = 1600 \text{mm}^2 \]
\[ A_2 = 16 \times 193 = 3088 \text{mm}^2 \]
\[ A_3 = 100 \times 16 = 1600 \text{mm}^2 \]
\[ \sum A = A_1 + A_2 + A_3 = 6288 \text{mm}^2 \]
\[ y_1 = 225 - 8 = 217 \text{mm} \]
\[ y_2 = \frac{193}{2} + 16 = 112.5 \text{mm} \]
\[ y_3 = \frac{16}{2} = 8 \text{mm} \]
\[ A_1 y_1 = 1600 \text{mm}^2 \times 217 \text{mm} = 347200 \text{mm}^3 \]
\[ A_2 y_2 = 3088 \text{mm}^2 \times 112.5 \text{mm} = 347400 \text{mm}^3 \]
\[ A_3 y_3 = 1600 \text{mm}^2 \times 8 \text{mm} = 12800 \text{mm}^3 \]
\[ \sum A y = A_1 y_1 + A_2 y_2 + A_3 y_3 = 707400 \text{mm}^3 \]
\[ \therefore \ \bar{y} = \frac{\sum A y}{\sum A} = \frac{707400 \text{mm}^3}{6288 \text{mm}^2} = 112.5 \text{mm} \]

\[ I_1 = \frac{b_1 d_1^3}{12} + A_1 (y_1 - \bar{y})^2 \]
\[ = \frac{100 \text{mm} \times 16 \text{mm}^3}{12} + 1600 \text{mm}^2 (217 \text{mm} - 112.5 \text{mm})^2 \]
\[ I_1 = 17506533.33 \text{mm}^4 \]

\[ I_2 = \frac{b_2 d_2^3}{12} + A_2 (y_2 - \bar{y})^2 \]
\[ = \frac{16 \text{mm} \times 193 \text{mm}^3}{12} + 1600 \text{mm}^2 (112.5 \text{mm} - 112.5 \text{mm})^2 \]
\[ I_2 = 9585409.33 \text{mm}^4 \]

\[ I_3 = \frac{b_3 d_3^3}{12} + A_3 (y_3 - \bar{y})^2 \]
\[ = \frac{100 \text{mm} \times 16 \text{mm}^3}{12} + 1600 \text{mm}^2 (112.5 \text{mm} - 8 \text{mm})^2 \]
\[ I_3 = 17506533.33 \text{mm}^4 \]
\[ \therefore I = I_1 + I_2 + I_3 = 44598475.99 \text{mm}^4 \]
\[ M_{\text{midspan}} = 76.25 \times 10^6 \text{Nmm} \]
\[ c = 112.5 \text{mm} \]
\[ \therefore \sigma_{\text{midspan}} = \frac{76.25 \times 10^6 \text{Nmm} \times 12.5 \text{mm}}{44.60 \times 10^6 \text{mm}^4} = 192.3 \text{N / mm}^2 \]

For minimum stress applied at midspan with \( P = 10 \text{ KN} \):
Minimum moment @ midspan, \( M_{\text{min}} = 5 \text{KN} \times 1.25 \text{m} = 6.25 \text{KNm} \)
\[ \sigma_{\text{min}} = \frac{6.25 \times 10^6 \text{Nmm} \times 12.5 \text{mm}}{44.60 \times 10^6 \text{mm}^4} = 17.5 \text{N / mm}^2 \]
\[ \therefore \]
\[ \sigma_{\text{max}} = 192.3 \text{N / mm}^2 \]
\[ \sigma_{\text{min}} = 15.5 \text{N / mm}^2 \]

\( \text{Stress Range, } \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 176.8 \text{N / mm}^2 \)
\[ \text{Mean Stress, } \sigma_{\text{m}} = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{207.8}{2} = 103.9 \text{N / mm}^2 \]
\[ \text{Stress Amplitude, } \sigma_{\Delta} = \frac{\Delta \sigma}{2} = 88.4 \text{N / mm}^2 \]

\textbf{Strain gauge results}

The strain values obtained during the experiment is shown below. The strain values were measured after every 100,000 cycles at a frequency of 1 Hz. 1 strain gauge was affixed at the top flange while another one was placed on the web within the zone of loading.

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Web</th>
<th>Flange</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17295</td>
<td>17050</td>
<td>192.3</td>
</tr>
<tr>
<td>100000</td>
<td>18450</td>
<td>16910</td>
<td>192.3</td>
</tr>
<tr>
<td>200000</td>
<td>18485</td>
<td>16900</td>
<td>192.3</td>
</tr>
<tr>
<td>300000</td>
<td>18490</td>
<td>16870</td>
<td>192.3</td>
</tr>
<tr>
<td>400000</td>
<td>18490</td>
<td>16885</td>
<td>192.3</td>
</tr>
<tr>
<td>500000</td>
<td>18480</td>
<td>16870</td>
<td>192.3</td>
</tr>
<tr>
<td>600000</td>
<td>18530</td>
<td>16900</td>
<td>192.3</td>
</tr>
<tr>
<td>700000</td>
<td>18010</td>
<td>17000</td>
<td>192.3</td>
</tr>
<tr>
<td>At failure 786000</td>
<td>17880</td>
<td>17400</td>
<td>192.3</td>
</tr>
</tbody>
</table>
Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until failure; the stress-strain curve yielded a straight line as shown below:

![Stress-Strain curve under cyclic loading](image)

**Figure 4.7 – Stress-strain curve**

**Relationship between Strain and cycles to failure**

The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at every 100,000 cycles of loading.

**Top flange**

![Top flange stress-strain](image)

**Figure 4.8 – Top flange**
As can be seen from the figure above, there was a sharp contraction after the first 100,000 cycles and afterwards stabilization. This shows that the top flange was under compression.

**Web**

![Web B](image)

Figure 4.9 – Web B

Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension. See figure 4.8 above.

**Failure Cycle:**

The beam failed by fracture at 786,000 cycles, which was approximately 218 hours of testing. The fracture occurred a small distance away from the point of loading. But since there was a carton packing of 120 mm long at the point of loading to help distribute the load, it can be said that failure occurred within the zone of loading.

![Failure Cycle](image)

Figure 4.10a
4.1.3 Grade 460W @ 0.50P

Specimen 3 of Grade 460W was loaded with 122 KN at the midspan until failure.

**Moment determination:**

\[ P = 122 \text{ KN} \]

\[ R_a = \frac{P}{2} = \frac{122 \text{ KN}}{2} = 61 \text{ KN} \]

Maximum moment (moment @ midpoint), \( M_{460} = 61 \text{ KN} \times 1.25 \text{m} = 76.25 \text{KNm} \)
Stress determination:
Considering the section at midspan directly under the point of loading where maximum stresses will be induced, as shown below.

\[
\sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I} c
\]

Where:

\(\sigma_{\text{midspan}}\) = maximum stress at midspan

\(M_{\text{midspan}}\) = Applied bending moment at midspan

\(C\) = Distance from neutral axis to surface of the specimen

\(I\) = Cross-sectional moment of inertia

\(\bar{y} = \frac{\sum A y}{\sum A}\)

\(A_1 = 100 \times 16 = 1600 \text{mm}^2\)

\(A_2 = 16 \times 155 = 2480 \text{mm}^2\)

\(A_3 = 100 \times 16 = 1600 \text{mm}^2\)

\(\sum A = A_1 + A_2 + A_3 = 5680 \text{mm}^2\)

\(y_1 = 187 - 8 = 179 \text{mm}\)

\(y_2 = \frac{155}{2} + 16 = 93.5 \text{mm}\)

\(y_3 = \frac{16}{2} = 8 \text{mm}\)
\[ A_1y_1 = 1600mm^2 \times 179mm = 286400mm^3 \]
\[ A_2y_2 = 2480mm^2 \times 93.5mm = 231880mm^3 \]
\[ A_3y_3 = 1600mm^2 \times 8mm = 12800mm^3 \]
\[ \sum Ay = A_1y_1 + A_2y_2 + A_3y_3 = 531080mm^3 \]
\[ \therefore \bar{y} = \frac{\sum Ay}{\sum A} = \frac{531080mm^3}{5680mm^2} = 93.5mm \]

\[ I_1 = \frac{b_1d_1^3}{12} + A_1(\bar{y} - \bar{y})^2 \]
\[ = \frac{100mm \times 16^3 mm^3}{12} + 1600mm^2 (179mm - 93.5mm)^2 \]
\[ I_1 = 11730533.33mm^4 \]

\[ I_2 = \frac{b_2d_2^3}{12} + A_2(\bar{y} - \bar{y})^2 \]
\[ = \frac{16mm \times 155^3 mm^3}{12} + 1600mm^2 (93.5mm - 93.5mm)^2 \]
\[ I_2 = 4965166.67mm^4 \]

\[ I_3 = \frac{b_3d_3^3}{12} + A_3(\bar{y} - \bar{y})^2 \]
\[ = \frac{100mm \times 16^3 mm^3}{12} + 1600mm^2 (93.5mm - 8mm)^2 \]
\[ I_3 = 11730533.33mm^4 \]
\[ \therefore I = I_1 + I_2 + I_3 = 28426233.33mm^4 \]

\[ M_{\text{midspan}} = 76.25 \times 10^6 Nmm \]
\[ c = 93.5mm \]

\[ \therefore \sigma_{\text{midspan}} = \frac{76.25 \times 10^6 Nmm \times 93.5mm}{28.43 \times 10^6 mm^4} = 251N/mm^2 \]

For minimum stress applied at midspan with P = 10 KN:
Minimum moment @ midspan, \( M_{\text{min}} = 5KN \times 1.25m = 6.25KNm \)

\[ \sigma_{\text{min}} = \frac{6.25 \times 10^6 Nmm \times 125mm}{28.43 \times 10^6 mm^4} = 27.5N/mm^2 \]
\[ \therefore \]
\[ \sigma_{\text{max}} = 251 \text{N/mm}^2 \]
\[ \sigma_{\text{min}} = 27.5 \text{N/mm}^2 \]

**Stress Range,** \( \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 223.5 \text{N/mm}^2 \)

**Mean Stress,** \( \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{278.5}{2} = 139.25 \text{N/mm}^2 \)

**Stress Amplitude,** \( \sigma_a = \frac{\Delta \sigma}{2} = 111.75 \text{N/mm}^2 \)

**Strain gauge results**

The strain values obtained during the experiment is shown below. The strain values were measured after every 100,000 cycles at a frequency of 1 Hz. 1 strain gauge was affixed at the top flange while another one was placed on the web within the zone of loading.

**Table 4.3 – Strain gauge results**

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Web</th>
<th>Flange</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17400</td>
<td>23975</td>
<td>251</td>
</tr>
<tr>
<td>50000</td>
<td>18100</td>
<td>21855</td>
<td>251</td>
</tr>
<tr>
<td>100000</td>
<td>18060</td>
<td>22035</td>
<td>251</td>
</tr>
<tr>
<td>150000</td>
<td>18000</td>
<td>22610</td>
<td>251</td>
</tr>
<tr>
<td>At Failure</td>
<td>19300</td>
<td>18290</td>
<td>251</td>
</tr>
</tbody>
</table>

Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until failure; the stress-strain curve yielded a straight line as shown below:
Figure 4.11 – Stress-strain curve

Relationship between Strain and cycles to failure

The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at every 50,000 cycles of loading.

Top flange

Figure 4.12 – Top flange
As can be seen from the figure above, there was a sharp contraction after the first 50,000 cycles and afterwards stabilization. This shows that the top flange was under compression.

**Web**

![Web 460W @ 122KN cyclic loading](image)

Figure 4.13 – Web B

Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension. See figure 4.11 above.

**Failure Cycle:**

The beam failed by fracture at 182,400 cycles, which was approximately 51 hours of testing. Fracture at a distance slightly away from the centre of the beam but still within the zone of loading as shown below.

![Figure 4.14a](image)
4.1.4 Grade 300W @ 0.75P

Specimen 4 of Grade 300W was loaded with 184 KN at the midspan until failure.

**Moment determination:**

\[ P = 184 \text{ KN} \]

Maximum moment (moment @ midpoint), \( M_{300} = 92 \text{KN} \times 1.25m = 115 \text{KNm} \)

**Stress determination:**

\[ R_i = \frac{P}{2} = \frac{184 \text{KN}}{2} = 92 \text{KN} \]
Considering the section at midspan directly under the point of loading where maximum stresses were induced, as shown below.

\[
\sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I} c
\]

Where:

\(\sigma_{\text{midspan}}\) = maximum stress at midspan

\(M_{\text{midspan}}\) = Applied bending moment at midspan

\(C\) = Distance from neutral axis to surface of the specimen

\(I\) = Cross-sectional moment of inertia

As previously determined,

\[
\therefore I = 57686709.33 \text{mm}^4
\]

\[
M_{\text{midspan}} = 76.25 \times 10^6 \text{Nm}
\]

\(c = 125 \text{mm}\)

\[
\therefore \sigma_{\text{midspan}} = \frac{115 \times 10^6 \text{Nm} \times 125 \text{mm}}{57.69 \times 10^6 \text{mm}^4} = 249 \text{ N/mm}^2
\]

For minimum stress applied at midspan with \(P = 10 \text{ KN}\):

Minimum moment @ midspan, \(M_{\text{min}} = 5 \text{KN} \times 1.25 \text{m} = 6.25 \text{KNm}\)

\[
\sigma_{\text{min}} = 13.5 \text{ N/mm}^2
\]
\[
\begin{align*}
\therefore \\
\sigma_{\text{max}} & = 249 N/ mm^2 \\
\sigma_{\text{min}} & = 13.5 N/ mm^2 \\
\text{Stress Range, } & \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 235.5 N/ mm^2 \\
\text{Mean Stress, } & \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{262.5}{2} = 131.25 N/ mm^2 \\
\text{Stress Amplitude, } & \sigma_a = \frac{\Delta \sigma}{2} = 117.75 N/mm^2
\end{align*}
\]

\textbf{Strain gauge results}

The strain values obtained during the experiment is shown below. The strain values were measured after every 100,000 cycles at a frequency of 1 Hz. 1 strain gauge was affixed at the top flange while another one was placed on the web within the zone of loading.

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Web</th>
<th>Flange</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16455</td>
<td>18330</td>
<td>249</td>
</tr>
<tr>
<td>100000</td>
<td>16600</td>
<td>16600</td>
<td>249</td>
</tr>
<tr>
<td>200000</td>
<td>16630</td>
<td>16640</td>
<td>249</td>
</tr>
<tr>
<td>300000</td>
<td>16610</td>
<td>16590</td>
<td>249</td>
</tr>
<tr>
<td>At failure 322023</td>
<td>16590</td>
<td></td>
<td>249</td>
</tr>
</tbody>
</table>

Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until failure; the stress-strain curve yielded a straight line as shown below:
Figure 4.15 – Stress-strain curve

Relationship between Strain and cycles to failure

The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at every 100,000 cycles of loading.

Top flange

Figure 4.16 – Top flange
As can be seen from the figure above, there was a sharp contraction after the first 100,000 cycles and afterwards stabilization. This shows that the top flange was under compression.

**Web - B**

![Graph showing strain over cycles]

Figure 4.17 – Web B

Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension.

**Failure Cycle:**

The beam failed by fracture at 322,023 cycles, which was approximately 89 hours of testing. Fracture occurred approximately at the middle of the beam within the zone of loading.

![Diagram showing fracture points]

Figure 4.18a
4.1.5 Grade 350W @ 0.75P

Specimen 5 of Grade 350W was loaded with 184 KN at the midspan until failure.

**Moment determination:**

\[ P = 184 \text{ KN} \]

\[
\begin{align*}
R_A &= \frac{P}{2} = \frac{184\text{KN}}{2} = 92\text{KN} \\
M_{350} &= 92\text{KN} \times 1.25m = 115\text{KNm}
\end{align*}
\]

**Stress determination:**
Considering the section at midspan directly under the point of loading where maximum stresses will be induced, as shown below.

\[ \sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I}c \]

Where:

- \( \sigma_{\text{midspan}} \) = maximum stress at midspan
- \( M_{\text{midspan}} \) = Applied bending moment at midspan
- \( C \) = Distance from neutral axis to surface of the specimen
- \( I \) = Cross-sectional moment of inertia

As already determined earlier,

\[ \therefore I = 44598475.99 \text{mm}^4 \]
\[ M_{\text{midspan}} = 115 \times 10^6 \text{ Nmm} \]
\[ c = 112.5 \text{mm} \]

\[ \therefore \sigma_{\text{midspan}} = \frac{115 \times 10^6 \text{ Nmm} \times 112.5 \text{mm}}{44.60 \times 10^8 \text{ mm}^4} = 290 \text{ N/mm}^2 \]

For minimum stress applied at midspan with \( P = 10 \text{ KN} \):

Minimum moment @ midspan, \( M_{\text{min}} = 5 \text{KN} \times 1.25 \text{m} = 6.25 \text{KNm} \)

\[ \sigma_{\text{min}} = 17.5 \text{ N/mm}^2 \]
\[ \sigma_{\text{max}} = 290 \text{ N/mm}^2 \]
\[ \sigma_{\text{min}} = 17.5 \text{ N/mm}^2 \]

Stress Range, \( \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 272.5 \text{ N/mm}^2 \)

Mean Stress, \( \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{307.5}{2} = 153.25 \text{ N/mm}^2 \)

Stress Amplitude, \( \sigma_a = \frac{\Delta \sigma}{2} = 136.25 \text{ N/mm}^2 \)

Strain gauge results

The strain values obtained during the experiment is shown below. The strain values were measured after 60 cycles at a frequency of 1 Hz when the structure deformed in its global axis. 1 strain gauge was affixed at the top flange while another one was placed on the web within the zone of loading.

Table 4.4 – Strain gauge results

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Flange</th>
<th>Web</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17610</td>
<td>17050</td>
<td>290</td>
</tr>
<tr>
<td>At failure 60</td>
<td>17185</td>
<td>19370</td>
<td>290</td>
</tr>
</tbody>
</table>

Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until deformation occurred; the stress-strain curve yielded a straight line as shown below:

![Stress-strain curve](image)

Figure 4.19 – Stress-strain curve
Relationship between Strain and cycles to failure

The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at the end of the 60 cycle deformation.

**Top flange**

![Graph showing relationship between strain and cycles to failure for Top flange](image)

Figure 4.20 – Top flange

As can be seen from the figure above, there was a sharp reduction after the 60 cycles of loading. This shows that the top flange was under compression.

**Web - B**

![Graph showing relationship between strain and cycles to failure for Web B](image)

Figure 4.21 – Web B
Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension.

**Failure Cycle:**
The beam failed by deformation at 60 cycles, which was approximately 1 minute of testing. Deformation of 30 mm maximum occurred at the centre of the beam.

![Figure 4.22 – Specimen at failure](image)

4.1.6 **Grade 460W @ 0.75P**
Specimen 6 of Grade 350W was loaded with 184 KN at the midspan until failure.

**Moment determination:**
P = 184 KN
\[ R_i = \frac{P}{2} = \frac{184 \text{KN}}{2} = 92 \text{KN} \]

Maximum moment (moment @ midpoint), \( M_{460} = 92 \text{KN} \times 1.25m = 115 \text{KNm} \)

**Stress determination:**

Considering the section at midspan directly under the point of loading where maximum stresses will be induced, as shown below.

\[
\sigma_{\text{midspan}} = \frac{M_{\text{midspan}}}{I} \cdot c
\]

Where:

\( \sigma_{\text{midspan}} \) = maximum stress at midspan

\( M_{\text{midspan}} \) = Applied bending moment at midspan

\( C \) = Distance from neutral axis to surface of the specimen

\( I \) = Cross-sectional moment of inertia

As already determined earlier,

\[ \therefore I = 28426233.33 \text{mm}^4 \]

\[ M_{\text{midspan}} = 115 \times 10^6 \text{Nmm} \]

\[ c = 93.5 \text{mm} \]
For minimum stress applied at midspan with \( P = 10 \text{ KN} \):

Minimum moment @ midspan, \( M_{\text{min}} = 5 \text{KNx1.25m} = 6.25 \text{KNm} \\
\sigma_{\text{min}} = 27.5 \text{N/mm}^2 \\
\therefore \sigma_{\text{max}} = 378 \text{N/mm}^2 \\
\sigma_{\text{min}} = 27.5 \text{N/mm}^2 \\
\text{Stress Range, } \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 350.5 \text{N/mm}^2 \\
\text{Mean Stress, } \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} = \frac{405.5}{2} = 202.75 \text{N/mm}^2 \\
\text{Stress Amplitude, } \sigma_a = \frac{\Delta \sigma}{2} = 175.25 \text{N/mm}^2 \\

Strain gauge results

The strain values obtained during the experiment is shown below. The strain values were measured after 50 cycles at a frequency of 1 Hz when the structure deformed in its global axis. 1 strain gauge was affixed at the top flange while another one was placed on the web within the zone of loading.

<table>
<thead>
<tr>
<th>Cycles to failure</th>
<th>Flange</th>
<th>Web</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18310</td>
<td>17780</td>
<td>378</td>
</tr>
<tr>
<td>At failure 50</td>
<td>17420</td>
<td>19650</td>
<td>378</td>
</tr>
</tbody>
</table>

Since there were no changes in stresses, i.e. a constant stress was applied to the structure throughout the testing until deformation occurred; the stress-strain curve yielded a straight line as shown below:
Relationship between Strain and cycles to failure
The changes in strain were monitored periodically using the strain gauges during the experiment. Microstrains were read off at the end of the 50 cycle deformation.

Top flange

Figure 4.24 – Top flange
As can be seen from the figure above, there was a sharp reduction after the 60 cycles of loading. This shows that the top flange was under compression.

**Web - B**

![Graph showing cyclic loading](image)

**Figure 4.25 – Web B**

Also, there was a sharp increment of the specimen at the web as measured using the strain gauges. This shows that the web was under tension.

**Failure Cycle:**

The beam failed by deformation at 50 cycles, which was approximately 1 minute of testing. Deformation of 70 mm maximum occurred at the centre of the beam.

![Image of specimen at failure](image)

**Figure 4.26 – Specimen at failure**
4.2 FURTHER DISCUSSIONS

4.2.1 Cycles to failure

It is observed that as the steel grades increase in yield stress with lower web depth, their cycle to failure reduces. As a summary, the tables below show the points and mode of failure for the various steel grades tested under the same load factor.

Under 0.5P = 122KN

Table 4.5

<table>
<thead>
<tr>
<th>Steel Grades</th>
<th>Failure Cycle</th>
<th>Testing Time</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>300W</td>
<td>1,200,000</td>
<td>333 hours</td>
<td>Buckling</td>
</tr>
<tr>
<td>350W</td>
<td>786,000</td>
<td>218 hours</td>
<td>Fracture</td>
</tr>
<tr>
<td>460W</td>
<td>182,400</td>
<td>51 hours</td>
<td>Fracture</td>
</tr>
</tbody>
</table>

Under 0.75P = 184KN

Table 4.6

<table>
<thead>
<tr>
<th>Steel Grades</th>
<th>Failure Cycle</th>
<th>Testing Time</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>300W</td>
<td>322,023</td>
<td>89 hours</td>
<td>Fracture</td>
</tr>
<tr>
<td>350W</td>
<td>60</td>
<td>1 minute</td>
<td>Buckling</td>
</tr>
<tr>
<td>460W</td>
<td>50</td>
<td>50 seconds</td>
<td>Buckling</td>
</tr>
</tbody>
</table>

As already been indicated, all the beams have the same moment capacity but varies in section dimension. The thickness and the flange dimension of all the specimen were kept constant, only the depth of flanges were changed in other to achieve equal capacity.

4.2.2 Determination of stresses at the point of failure

Stresses will be determined for 300W @ 184 KN, 350 @ 122 KN and 460W @ 122 KN which were the beams that failed by fracture.
From previous calculations,

\[ I = 57.69 \times 10^6 \text{mm}^4 \]
\[ c = 125 \text{mm} \]

\[ \therefore \sigma_{1,24} = \frac{114.08 \times 10^6 \text{Nmm} \times 125 \text{mm}}{57.69 \times 10^6 \text{mm}^4 \times 125 \text{mm}} = 247.2 \text{N/mm}^2 \]
\[ \sigma_{1.10} = \frac{M_{1.10}}{I} \cdot c \]

From previous calculations,
\[ I = 44.6 \times 10^6 \text{ mm}^4 \]
\[ c = 112.5 \text{ mm} \]
\[ \therefore \sigma_{1.10} = \frac{67.1 \times 10^6 \text{ Nmm}}{44.6 \times 10^6 \text{ mm}^4} \cdot 112.5 \text{ mm} = 169.3 \text{ N/mm}^2 \]

460W @ 122 KN

\[ P = 122 \text{ KN} \]
\[ R_A = R_b = \frac{122 \text{ KN}}{2} = 61 \text{ KN} \]
\[ M_{1.21} = 61 \text{ KN} \cdot 1.21 \text{ m} = 73.81 \text{ KNm} \]
\[ \sigma_{1.21} = \frac{M_{1.21}}{I} \cdot c \]

From previous calculations,
\[ I = 28.43 \times 10^6 \text{ mm}^4 \]
\[ c = 93.5 \text{ mm} \]
\[ \therefore \sigma_{1.21} = \frac{73.81 \times 10^6 \text{ Nmm}}{28.43 \times 10^6 \text{ mm}^4} \cdot 93.5 \text{ mm} = 243 \text{ N/mm}^2 \]

Summarily, the moment and stress at the point of fracture as compared to the maximum moment and stresses applied at midspan are represented in the table below:
Table 4.5

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum Moment @ midspan</th>
<th>Moment at point of failure</th>
<th>Maximum Stress @ midspan</th>
<th>Stress at point of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 @ 184 KN</td>
<td>115 KNm</td>
<td>114.08 KNm</td>
<td>249 N/mm²</td>
<td>247.2 N/mm²</td>
</tr>
<tr>
<td>350 @ 122 KN</td>
<td>76.25 KNm</td>
<td>67.1 KNm</td>
<td>192.3 N/mm²</td>
<td>169.3 N/mm²</td>
</tr>
<tr>
<td>460 @ 122 KN</td>
<td>76.25 KNm</td>
<td>73.81 KNm</td>
<td>251 N/mm²</td>
<td>243 N/mm²</td>
</tr>
</tbody>
</table>

**Stress Table:**

Table 4.6 – Stress Table

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum Stress, $\sigma_{\text{max}}$ (N/mm²)</th>
<th>Minimum Stress, $\sigma_{\text{min}}$ (N/mm²)</th>
<th>Stress Range, $\Delta \sigma$ (N/mm²)</th>
<th>Mean Stress, $\sigma_{\text{m}}$ (N/mm²)</th>
<th>Stress Amplitude, $\sigma_{\text{m}}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300@122KN</td>
<td>165</td>
<td>13.5</td>
<td>151.5</td>
<td>89.25</td>
<td>75.75</td>
</tr>
<tr>
<td>350@122KN</td>
<td>192.3</td>
<td>15.5</td>
<td>176.8</td>
<td>103.9</td>
<td>88.4</td>
</tr>
<tr>
<td>460@122KN</td>
<td>251</td>
<td>27.5</td>
<td>223.5</td>
<td>139.25</td>
<td>111.75</td>
</tr>
<tr>
<td>300@184KN</td>
<td>249</td>
<td>13.5</td>
<td>235.5</td>
<td>131.25</td>
<td>117.75</td>
</tr>
<tr>
<td>350@184KN</td>
<td>290</td>
<td>17.5</td>
<td>272.5</td>
<td>153.25</td>
<td>136.25</td>
</tr>
<tr>
<td>460@184KN</td>
<td>378</td>
<td>27.5</td>
<td>350.5</td>
<td>202.75</td>
<td>175.25</td>
</tr>
</tbody>
</table>

4.2.3 **Relationship of graph curves**

As can be seen in the above graphs plotted, the behaviour of the strain gauge is similar to each other.

All the strain measurements were similar (see figures 4.2, 4.8, 4.12, 4.16, 4.20 and 4.24), i.e. there was a visible contraction in length after the first 100,000 cycles of testing, then stabilization. This notably shows that the flanges were subjected to initial compression. The stabilization was a fluctuation between contractions and expansions as the beam was been dynamically loaded. This shows that the beam was experiencing both strain hardening and softening as it was been loaded.

Also, all the strain gauges placed on the web, figures 4.3, 4.4, 4.5, 4.16, 4.9, 4.13, 4.17, 4.21 and 4.25 showed similar behaviour, i.e. there was
a visible expansion in length after the first 100,000 cycles of testing, then stabilization. This notably shows that the webs were subjected to initial tension. The stabilization was a fluctuation between contractions and expansions as the beam was been dynamically loaded. In other words, the beam was experiencing both strain hardening and softening as it was been loaded.

The values of the strain gauges after failure seem outrageous and should be neglected in design analysis since they were obtained after failure. This was caused by a snap of the strain gauges since the failure instantaneously.

4.2.4 Relationship of the zone of failure

As can be seen from the failure modes, all the specimens failed, whether fracture or deformation, within the zone of loading. The stresses induced at the point of failure where close to the maximum stresses induced at the midspan of the specimens. Even the specimen 1 (300W @ 122 KN) which failed by global buckling, the maximum deformation occurred at the zone of loading.