Evaluating the Efficiency of Strengthening Hot-Rolled I-Sectioned Steel Beams by using Additional Plates and Inclined Stiffeners with Various Widths

Asst. Prof. Dr. Ahmed S. D. AL-Ridha*, Lec. Ali A. Abbood1, Asst. Prof. Ali F. Atshan2.

1Department of Civil Engineering / College of Engineering / Mustansiriya University. Baghdad 10001, Iraq
2Department of Water Resources Engineering / College of Engineering / Mustansiriya University. Baghdad 1001, Iraq

*Corresponding author’s e-mail: ahmedsahibdiab@yahoo.com

Abstract: In this research, an attempt has been made to study the efficiency of strengthening hot-rolled I-sectioned steel beams by using additional steel plates welded at top and bottom flanges and inclined stiffeners with various widths welded at both sides of the web. This addition was incorporated to increase the moment of inertia about x and y axes (I_{x} and I_{y}) in order to reduce the vertical mid-span deflection as well as the horizontal strain and to prevent (or at least postpone) the occurrence of the lateral buckling. It was found that, the basic governing role of the additional top and bottom steel plates was to enlarge (I_{x}) for the purpose of decreasing the vertical mid-span deflection and the horizontal strain, while the major contribution of the inclined stiffeners was found that primarily its configuration provides some kind of lateral support and secondarily through increasing (I_{y}). It was also found that the usage of this type of strengthening leads to increase the ultimate load value in addition to the pre-mentioned reduce in deflection and strain. On the other hand, the failure mode is noticed to be changed from “lateral buckling” type (for the non-strengthened beams) to a “plastic hinge” type at mid-span (for the strengthened beams) which is attributed to letting the strengthened beam attain its full flexural capacity through preventing (or postponing) the occurrence of lateral buckling.

1. Introduction
In steel beams, a beam loaded predominantly in flexure would attain its full moment capacity if the local and lateral instabilities of the beam are prevented. If the laterally unrestrained length of the compression flange of the beam is relatively long, then a phenomenon, known as lateral buckling or lateral torsional buckling of the beam may take place. The beam will fail quite before it attains its’ full flexural capacity. Lateral buckling can be prevented, if adequate restraints are provided to the beam in the plane of the compression flange. Beams may also fail by local buckling or local failure (shear yielding of web, local crushing of web or buckling of thin flanges). These may be prevented by providing stiffened additional flange plates [1].

The current work presents a study of strengthening steel beams by additional steel plates (welded at top and bottom flanges) as well as inclined stiffeners (welded at both sides of the web) for the purpose of...
preventing or postponing the occurrence of lateral buckling besides the use of a vertical stiffener (welded at both sides of the web) placed at supports and mid-span locations for all strengthened and non-strengthened beams, these additional parts were incorporated to enable the strengthened beam attain its’ full moment capacity before the occurrence of lateral buckling failure.

Only few researchers have studied the effect of inclined stiffeners on hot-rolled I-sectioned steel beams. “Yang and Lui”(2012) have studied steel beams strengthened with inclined stiffeners, the outcomes have shown that the presence of such stiffeners offers a noticeable increase in the lateral torsional buckling load of the beams. The analysis results of “Yang and Lui”(2012) work have also shown that the amount of increase in lateral torsional buckling capacity is mostly dependent on the the inclined stiffeners location and the lateral unsupported length of the beam. It has been found that the beneficial effect of the stiffeners is primarily related to their location on the beam and that a distance of (0.1L) to (0.2L) measured from the beam ends would be considered as optimal for the stiffeners. It has also been found that the beneficial effect becomes more prominent for longer beams and when the vertical inclination angle increases [2].

“Prabha and Emilreyan”(2018) have studied the behavior of I-sectioned steel beams strengthened by vertical, horizontal and inclined stiffeners (with various shapes) along the beam length. The results have revealed a considerable improvement in failure load and deflection values [3].

Longitudinal stiffeners in hot-rolled beams are mostly used to reinforce the cutout regions of coped beams [4],[5]. Several investigators have studied the efficiency of strengthening steel plate girders by vertical and horizontal stiffeners such as [6-23], and others like [13-23] have studied the use of inclined stiffeners in addition to vertical and horizontal stiffeners in plate girders. Many researchers studied the effect of the additional plate [24-26] . The experimental results have revealed that the ultimate carrying capacity of the tested specimens is affected by the cover plate length and area and the proposed welding technique, the proposed welding technique (used to weld cover plate while under load) was found to be effective in increasing the load capacity by up to 5.7 % and reducing the maximum deflection by 30.7 % [24]. The test results have also revealed that the (width / thickness) ratio of the bonded plate should be greater than 20. The surfaces of the beam and plate should be cleaned by suitable cleaning methods such as for instance sand-blasting or mechanical clattering [25], and the bonding work should be performed with care as well [25]. This study have strongly recommended that end anchorage should be applied to the bonded plate in tension face and the use of bonded plate in compression side is prohibited. Additional plate in compression face should be attached to the original beam by a continuous welding.[ 26].

Many researchers such as ; [27] and [28] have studied the efficiency of strengthening steel beams with vertical stiffeners and carbon fiber.

2. Research Significance.

This research studies the efficiency of adding vertical and inclined stiffeners at both sides of the beam web for the purpose of preventing (or postponing) the lateral buckling to allow the beam to attain its full flexural capacity, as well as adding additional steel plates at top and bottom flanges of the beam for the purpose of increasing the beam flexural stiffness (represented by reducing the mid-span deflection induced by enlarging the moment of inertia Ix,x).

3. Experimental work

3.1 Structural Elements.

3.1.1 I-Section Steel Beam,

Table (1) displays the detailed description (i.e. the dimensions and properties) of the tested beams’ cross sections.
Table (1) : Dimensions and characteristics of steel beams’ section *

| Dimensions (mm) | H = 100 | B = 55 |
|----------------|---------|--------|
| t₁ = 4.1       |         |        |
| t₂ = 5.7       |         |        |
| Radius of curvature (mm) | r = 7 |
| Cross sectional area (mm²)   | A₅ = 1030 |
| Mass per meter (Kg/m)         | 8.1    |
| Moment of inertia (mm⁴ x 10³) | Iₓₓ = 1710 |
|                     | Iᵧᵧ = 159 |
| Yielding strength (fᵧ) (MPa)  | 250   |
|                     | 400   |
| Ultimate tensile strength (fᵤ) (MPa) |       |

*Supplied by the manufacturer

3.1.2 Additional Steel Plates, Vertical and Inclined Stiffeners.

Table (2) presents the detailed description (i.e. the dimensions and numbers) of additional steel plates, vertical and inclined stiffeners as well as the inclination angle of the inclined stiffeners.

Table 2. Specifications of Additional plates and Inclined stiffeners.

| Designation | Vertical stiffeners (mm) | No. of vertical stiffeners | Additional plates (mm) | No. of plates | Inclined stiffeners (mm) | No. of inclined stiffeners | Angle (deg.)* |
|-------------|--------------------------|----------------------------|------------------------|--------------|--------------------------|----------------------------|---------------|
| Beam (B1)  | 86 × 22 × 6              | 6                          |                        |              |                          |                            |               |
| Beam (B2)  | 86 × 22 × 6              | 6                          | 500 × 12.5 × 3         | 2            | 250 × 12.5 × 3           | 4                          | ≈ 21°         |
| Beam (B3)  | 86 × 22 × 6              | 6                          | 500 × 25 × 3           | 2            | 250 × 25 × 3            | 4                          | ≈ 21°         |

* The angle is computed between the inclined stiffener and the flange (horizontal line).

Note : Additional plates are welded to the flange, while the inclined and vertical stiffeners are welded to the beam web.

The direct-tension test of a typical (of the used steel) specimen was carried out at the laboratory of Mustansiriyah University / College of engineering / Civil engineering department by using universal hydraulic machine with a capacity of (1200 KN) as shown in Figure (1). The test was performed according to ASTM A370-2014[29] and test results are recorded at Table (3).

Table 3. Characteristics of a tested specimen based on direct tension test.

| Dimension | X | Y |
|-----------|---|---|
| H         |   |   |
| B         |   |   |
| t₁        |   |   |
| t₂        |   |   |
| r         |   |   |
| A₅        |   |   |
| Iₓₓ       |   |   |
| Iᵧᵧ       |   |   |
| fᵧ        |   |   |
| fᵤ        |   |   |
| Standard Specification | Yielding Strength $[F_y]$ (MPa) | Ultimate Tensile Strength $[F_u]$ (MPa) | Elongation at Rupture (in 200 mm) (%) |
|------------------------|-------------------------------|----------------------------------------|--------------------------------------|
| Test Results of present study steel | 265                           | 410                                    | 22.6                                  |
| ASTM–Limitations for A36–mild–low carbon steel | $\geq 250$                      | $\geq 400$                             | $\geq 20$                             |

**Figure 1.** Direct tension test (i) The steel plate specimen. (ii) Specimen dimensions. (iii) Testing machine.

3.2 Details of the Tested Beams.
In the present work, three steel beams (B1, B2 and B3) were studied, each beam has six vertical stiffeners with (86×22×6)mm dimensions each, placed at supports and mid-span (at both sides of the web) in order to prohibit the occurrence of local failure at these locations. Beam (B1) is considered as the reference beam (since it wasn’t strengthened by additional plates and inclined stiffeners), and beam (B2) was strengthened by two additional plates at top and bottom flanges each with (500×12.5×3)mm dimensions and four inclined stiffeners (of 21° inclination angle) at both sides of the web with (250×12.5×3)mm dimensions each, while beam (B3) was strengthened by two additional plates at top and bottom flanges with (500×25×3)mm dimensions each, and four inclined stiffeners (of 21° inclination angle) at both sides of the web with (250×25×3)mm dimensions each, as shown in Figure (2).
3.3 Description of the Testing Procedure.

All beams were tested as simply supported beams loaded with one point load at the middle of the beam span. During the test period the deflection of the beam was measured at the middle of beams’ span by using a dial gauge. Longitudinal strain was also measured throughout the test period using a TML—strain gauge fixed at the upper face of the bottom flange shifted by (40 mm) from mid-span. The readings of the dial gauge and the strain gauges were recorded for each (5 KN) load increment (from the starting of load application until the occurrence of failure). Fig.(3) shows the testing details and instruments of a typical tested beam.
4. Results and Discussion

4.1 Effect of Additional Plates and Inclined Stiffeners with Various Widths on Load–Deflection Response.

Figure (4) displays the load-deflection response of the tested beams (B1), (B2), and (B3). In this figure, the load-deflection response shows that beams became stiffer when additional plates and inclined stiffeners were added, this response was magnified and became more obvious when the width of additional plates and inclined stiffeners is increased.

The deflection results in this figure reveal that beam (B2) is stiffer than the reference beam (B1), while beam (B3) has shown a more stiff behavior than (B1) and (B2). The reason of this behavior may be attributed to the combined effect of the additional plates at top and bottom flanges which act to increase the moment of inertia of the beam cross section about x-axis, in addition to the contribution of the inclined stiffener in increasing the stiffness of the web and hence increasing the moment of inertia of the whole section about x-axis.

![Figure 4. Load-Deflection response for beams B1, B2 and B3.](image)

4.2 Effect of Additional Plates and Inclined Stiffeners with Various Widths on Load-Strain Response.

Figure (5) show the load-strain response of the tested beams (B1), (B2), and (B3). In this figure, load-strain response reveals that the beams became stiffer when additional plates and inclined stiffeners were added, and this behavior was magnified and became more clear when the width of additional plates and inclined stiffeners is increased.

The strain results in this figure reveal that beam (B2) is stiffer than the reference beam (B1), while beam (B3) has shown a more stiff behavior than (B1) and (B2). The reason of this behavior is the same reason mentioned in the previous section (4-1).
4.3 Effect of Additional Plates and Inclined Stiffeners with Various Widths on Ultimate Load.

Figure (7) gives the ultimate load values of the tested beams (B1), (B2) and (B3). It shows that when adding additional plates (at top and bottom flanges) as well as the inclined stiffeners (at the both side of the web), the ultimate load was enlarged, and the percentage of this enlargement is increased with increasing the width of additional plates and inclined stiffeners. This increase in ultimate load may be attributed to the combined effect of the additional steel plates at top and bottom flanges which act to increase the moment of inertia of beam section about (x & y) axes, and the role of the inclined stiffener in preventing (or at least postponing) lateral buckling.

The role of the inclined stiffeners could be summarized in the following points:

1. They increase the moment of inertia of the beam cross section about y-axis ($I_{y}$) through:
   - Increasing the moment of inertia of beam section about y-axis ($I_{y}$) more than an identical cross sectional area of additional top and bottom plates do.
   - (b) The vertical thickness of the inclined stiffener resulted from cutting the strengthened beam by a vertical section will be about 7.33% greater than its actual thickness, which will lead to enlarge its contribution in increasing ($I_{y}$), see figure (6).

2. The configuration of the inclined stiffener has provided some kind of lateral support when placed at mid-span in an inverted (V) configuration such that its vertex is upward (i.e. at the point of application of the concentrated load) as shown in figure (6).

1. For the both reasons mentioned in the above two points (1) and (2), the basic role of the inclined stiffeners is that they act to postpone the occurrence of the lateral buckling and hence lead to increase the amount of ultimate load of the strengthened beam.
Figure 6. Configuration of additional plates, vertical and inclined stiffeners at mid-span.

Figure 7. Ultimate load values for beams B1, B2 and B3.

4.4 Effect of Additional Plates and Inclined Stiffeners with Various Widths on Failure Mode Type. Figure (8) shows the failure mode shapes of the tested beams (B1),(B2) and (B3) . From this figure it can be seen that the failure mode has been changed from “lateral buckling mode” (as for the reference beam B1 ) to a “plastic hinge failure mode” at mid-span of beams (B2) and (B3) (strengthened by additional plates at top and bottom flanges and inclined stiffeners) . This change in failure mode could be interpreted by the significant role of the inclined stiffeners in preventing (or postponing) lateral buckling as been previously mentioned.
Figure 8. Failure mode shapes for beams B1, B2 and B3.

5. Conclusions.
- When additional plates at top and bottom flanges besides the inclined stiffeners are added to the beam, the load-deflection and load-strain responses have revealed that the beam becomes stiffer as compared with the reference beam. This response is magnified and becomes more obvious when the width of additional steel plate is increased.
- When adding additional plates and inclined stiffeners, the mode of failure was noticed to be changed from “lateral buckling” mode to a “plastic hinge” underneath the concentrated load (at mid-span).
- The major role of the inclined stiffener in preventing (or at least postponing) the lateral buckling can be explained as: Its configuration primarily provides some kind of lateral support to the beam at mid-span location and secondarily increases ($I_{yy}$) through the increase in ($A_g$) resulted from cutting the beam by a vertical section (rather than that resulted from a perpendicular one).
- The essential effect of the inclined stiffener is found to be in increasing the ultimate load through preventing (or at least postponing) the lateral buckling, while its effect is small in decreasing the strain and deflection. On the other hand, the essential effect of the additional plates is noticed to be in “extremely” decreasing the strain and deflection, while the effect of these plates is smaller in preventing lateral buckling.

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