

MEEN 368: Solid Mechanics in Mechanical Design
Design of a Bolted Splice Repair for a Broken I-Beam

DESIGN PROJECT REPORT



*On my honor, as an Aggie, I have neither given nor received
unauthorized aid on this academic work.*

Group 6 / Date of Submission: 4/27/2026	
Name	Signature
Jason Bonitatibus	
Golden Zhang	GZ
John Peterman	
Donghoon Han	DH

Introduction

Bolted splice repairs are often used to restore load transfer across damaged structural members. In this project, a fractured I-beam is repaired using two web-mounted splice plates fastened via bolts. The beam is modeled as simply supported with a concentrated load at midspan, where the fracture is located. The splice region must restore strength and stiffness due to the maximum bending moment. In this report, two repair designs are evaluated: a compact design with thinner, shorter plates and fewer, smaller bolts, and a stronger design with thicker, longer plates and more, larger bolts. We compare how plate size, bolt number, bolt diameter, and bolt spacing affect stress concentration, load transfer, and deflection¹.

The beam is studied in two orientations: load applied parallel to the web, and load applied normal to the web. Since the I-section has different second moments of area about its principal axes, these orientations produce different bending stiffness and repair demands. This project combines analytical beam calculations, finite element analysis, and physical testing of 3D-printed PLA specimens to compare the two splice designs and identify which provides better structural performance.

Beam and Connection Geometry

The repaired member considered in this project is a simply supported I-beam with a total span of 250 mm, modeled as two halves of 125 mm joined at a fracture located at midspan. Figure 1(a) represents the repaired beam assembly, while Figure 1(b) shows the cross-sectional dimensions of the I-beam. Since the fracture is placed at the center section, the repair is evaluated at the location of maximum bending moment, making it a meaningful case for both analytical and computational study.

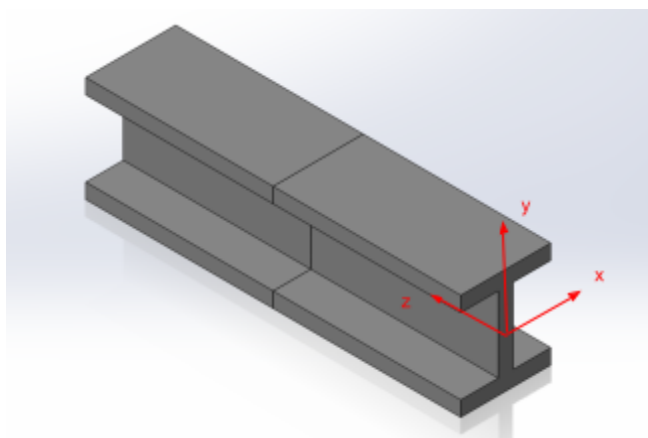


Figure 1(a): Joined I-beam Structure

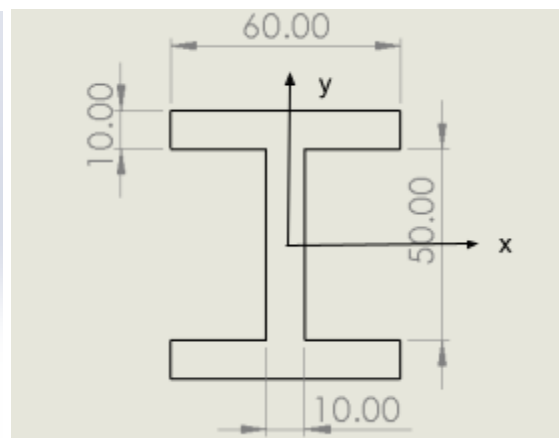


Figure 1(b): I-beam Cross Section (mm)

As shown in Figure 1(b), the beam uses a symmetric I-shape with dimensions listed below;

- b_f : flange width = 60 mm
- t_f : flange thickness = 10 mm
- t_w : web thickness = 10 mm
- h_w : clear web height = 50 mm
- h : total beam depth = 70 mm
- L : total beam span = 250 mm

This cross-section was chosen because it captures the essential behavior of an I-beam while remaining simple enough for analysis and finite element modeling. In particular, the section has different second moments of area about its principal axes, which is important because the project requires the repaired beam to be studied in two orientations: load normal to the web and load parallel to the web. These two orientations lead to different bending stiffness and, therefore, different repair demands.

The repair concept is illustrated in Figures 2(a) and 2(b) and consists of two rectangular splice plates attached to the web, one on each side. The web-only splice was selected to meet the simplified repair configuration requirements and to keep the load path clear. In this configuration, the bolts primarily transfer shear load through the web splice region, while the splice plates bridge the fractured section and help redistribute load across the connection. Since the I-beam flanges are not directly spliced, the repair is not assumed to recreate a perfectly continuous intact beam, but it is expected to restore the load-carrying capacity only partially. This makes comparison of stress concentration and stiffness recovery especially important.

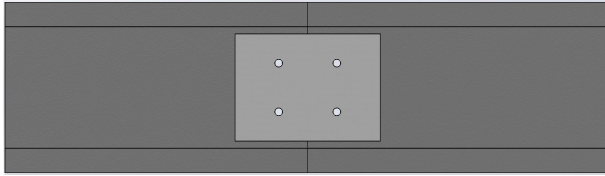


Figure 2(a): Splice Design Candidate 1

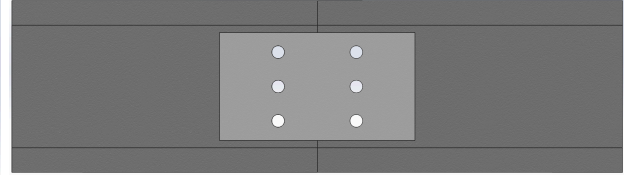


Figure 2(b): Splice Design Candidate 2

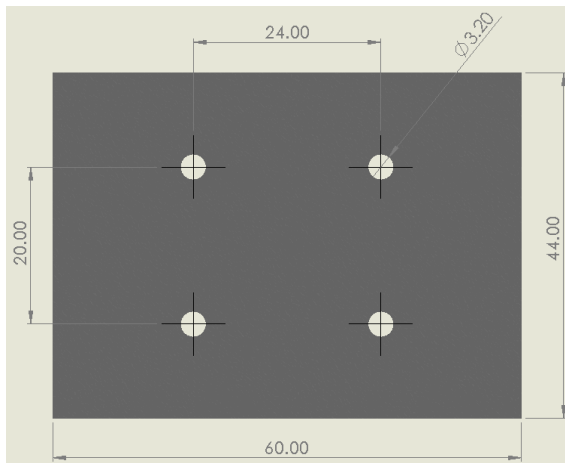


Figure 3(a): 4 Bolt Splice Dimensions (mm)

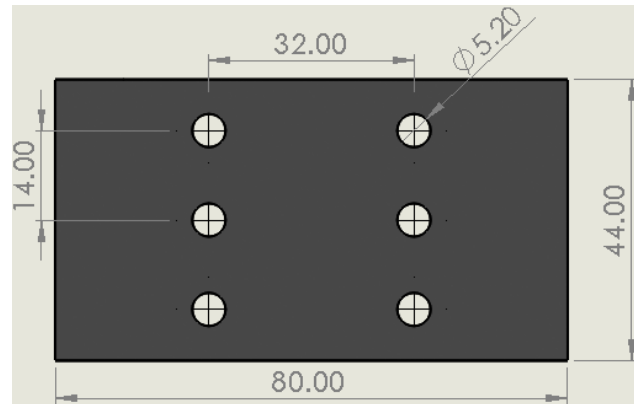


Figure 3(b): 6 Bolt Splice Dimensions (mm)

The splice plates were intentionally kept within the web region, and a small clearance was maintained between the top and bottom edges of the splice plates and the beam flanges so that the plates do not contact the flanges directly. This choice avoids unintended flange support and prevents the connection from becoming artificially stiff in the analytical model or finite element model. Rectangular splice plates were selected because they provide clean dimensions, straightforward bolt placement, and a clear basis for comparing the two designs.

Two candidate splice designs were determined, and their detailed dimensions are shown in Figures 3(a) and 3(b). For both designs, the splice plate dimensions are defined as follows: t_p is the splice plate thickness, l_p is the splice plate length measured along the beam axis, and h_p is the splice plate height measured vertically within the web region. The bolt geometry is defined by d , the nominal bolt diameter, and d_h , the hole diameter. The total number of bolts is denoted by n . Bolt locations are described relative to the fracture plane and the web mid-height, with s_x denoting horizontal bolt spacing, s_y denoting vertical bolt spacing, e_x the horizontal edge distance from the outer bolt center to the splice plate end, and e_y the vertical edge distance from the outer bolt center to the splice plate edge.

For Design 1, a compact baseline repair was selected to represent the smaller and lighter splice configuration. This design uses a symmetric 2x2 bolt pattern and a thinner, shorter plate so that it remains easy to fabricate and introduces less net-section reduction in the web. At the same time, because it uses fewer and smaller bolts and a smaller splice plate, it is expected to carry higher force per bolt and provide lower stiffness recovery than the larger candidate.

- $n_1 = 4$
- $d_1 = 3 \text{ mm (M3)}$
- $d_{h1} = 3.2 \text{ mm}$
- $s_{x1} = 24 \text{ mm}$
- $s_{y1} = 20 \text{ mm}$
- Bolt coordinates: $(x, y) = (\pm 12, \pm 10) \text{ mm}$ (from the splice center)
- $t_{p1} = 4 \text{ mm}$
- $l_{p1} = 60 \text{ mm}$
- $h_{p1} = 44 \text{ mm}$
- $e_{x1} = 18 \text{ mm}$
- $e_{y1} = 12 \text{ mm}$

The selected layout places the bolt group symmetrically about both the fracture plane and the web mid-height, which avoids unnecessary eccentricity and makes the analytical interpretation more straightforward.

For Design 2, a more robust repair was selected to represent the stronger and stiffer splice configuration. This design uses more bolts, larger bolt diameter, and a thicker and longer plate in order to improve load transfer across the fractured section. Compared with Design 1, Design 2 is expected to reduce the average force carried by each bolt, lower bearing stress at the bolt holes,

and provide a stiffer connection that better limits relative rotation of the two beam halves at the fracture.

- $n_1 = 6$
- $d_2 = 5 \text{ mm (M5)}$
- $d_{h2} = 5.2 \text{ mm}$
- $s_{x2} = 32 \text{ mm}$
- $s_{y2} = 14 \text{ mm}$
- Bolt coordinates: $(x, y) = (\pm 16, 14), (\pm 16, 0), (\pm 16, -14) \text{ mm}$
- $t_{p2} = 6 \text{ mm}$
- $l_{p2} = 80 \text{ mm}$
- $h_{p2} = 44 \text{ mm}$
- $e_{x2} = 24 \text{ mm}$
- $e_{y2} = 8 \text{ mm}$

The 2x3 bolt arrangement was selected because it remains symmetric and mechanically clear while providing a larger bolt group and longer transfer region than Design 2. This makes it a suitable candidate for evaluating how increased bolt number and splice plate size influence the stress distribution and stiffness of the repaired beam. Overall, the two candidate geometries provide a meaningful comparison between a compact repair and a stronger repair.

Analytical Investigation

- Problem Setup and Assumptions

The repaired structure is modeled as a simply supported I-beam of total span $L = 250 \text{ mm}$, subjected to a concentrated load $F = 275 \text{ N}$ (assumed load) at midspan. The beam is fractured at the center section and repaired using two splice plates attached to the web, one on each side. Two loading orientations are considered. In the first orientation, as represented by Figure 4(a), the beam is positioned such that the applied load acts parallel to the web. In this configuration, the beam bends about the centroidal x-axis, and the response is governed by I_x , the second moment of area about the horizontal centroidal axis. In the second orientation, Figure 4(b) the beam is rotated such that the applied load acts normal to the web. In this configuration, the beam bends about the centroidal y-axis, and the response is governed by I_y , the second moment of area about the vertical centroidal axis. Since the cross-section has different second moments of area about these two axes, the two loading cases produce different bending stresses, deflections, and repair demands.

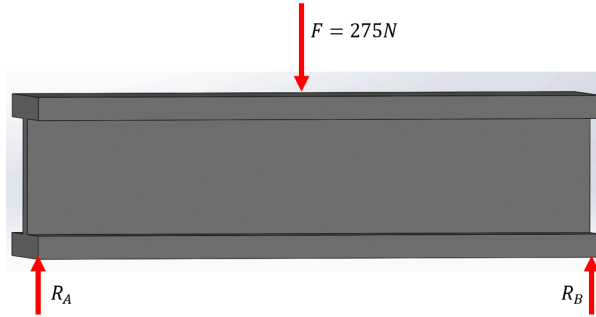


Figure 4(a): Load Parallel to Web

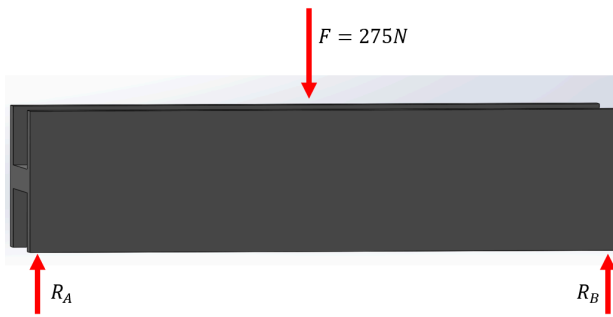


Figure 4(b): Load Normal to Web

The analytical model assumes linear elastic behavior, small deflection beam theory, and a simplified splice load path in which the bolts primarily transfer through the web while the splice plates redistribute load across the fracture and provide partial rotational restraint. Since the flanges are not directly spliced, the repair is not expected to restore the full stiffness of the intact beam.

- Intact Beam Reactions, Shear Force, and Bending Moment

From static equilibrium, the support reactions are equal:

$$R_A = R_B = \frac{F}{2} = \frac{275N}{2} = 137.5 N$$

The internal shear force is therefore

$$V(z) = + 137.5 N \quad 0 < z < 125 mm$$

$$V(z) = - 137.5 N \quad 125 < z < 250 mm$$

For the left half of the beam, the internal bending moment is

$$M(z) = R_A z = 137.5 z N \cdot mm$$

At the fracture section located at midspan,

$$M_{fracture} = M\left(\frac{L}{2}\right) = \frac{FL}{4} = \frac{137.5N(250mm)}{4} = 8593.75 N \cdot mm$$

The section shear immediately adjacent to the fracture is

$$V_{fracture} = \frac{F}{2} = 137.5 N$$

Thus, the repair must be designed at the location of maximum bending moment while also transferring a section shear of 137.5 N across the fracture. This is the main analytical demand used for the splice and bolt checks.

- Cross-Sectional Properties of the I-beam

The cross-section is symmetric, so the neutral axis passes through the section center.

Cross-sectional area:

$$A = 2(b_f t_f) + t_w h_w = 1700 \text{ mm}^2$$

Second moment of area about the x-axis

$$I_x = 2\left(\frac{b_f t_f^3}{12} + b_f t_f \left(\frac{h_w + t_f}{2}\right)^2\right) + \frac{t_w h_w^3}{12} = 1.194 \times 10^6 \text{ mm}^4$$

Second moment of area about the y-axis

$$I_y = 2\left(\frac{t_f b_f^3}{12}\right) + \frac{h_w t_w^3}{12} = 3.642 \times 10^5 \text{ mm}^4$$

Since $I_x > I_y$, I_x is the stronger-axis second moment of the area.

Section modulus about the x-axis,

$$S_x = \frac{I_x}{c_x} = \frac{I_x}{h/2} = \frac{1.194 \times 10^6 \text{ mm}^4}{35 \text{ mm}} = 3.412 \times 10^4 \text{ mm}^3$$

Section modulus about the y-axis,

$$S_y = \frac{I_y}{c_y} = \frac{I_y}{b_f/2} = \frac{3.642 \times 10^5 \text{ mm}^4}{30 \text{ mm}} = 1.214 \times 10^4 \text{ mm}^3$$

Again, $S_x > S_y$, confirming that the I cross-section is much stiffer and stronger about the x-principal-axis than the y-principal-axis, justifying the project requirement of testing two different loading orientations.

- Intact Beam Stress and Deflection in the Two Orientations

The bending stress is defined as

$$\sigma = \frac{Mc}{I} = \frac{M}{s}$$

The maximum bending stress for the load parallel to the web case (the strong-axis bending) is

$$\sigma_{\text{max, Parallel}} = \frac{M_{\text{fracture}}}{S_x} = \frac{8593.75 \text{ N}\cdot\text{mm}}{3.412 \times 10^4 \text{ mm}^3} = 0.252 \text{ MPa}$$

For the load normal to the web case (the weak-axis bending) is

$$\sigma_{\text{max, Normal}} = \frac{M_{\text{fracture}}}{S_y} = \frac{8593.75 \text{ N}\cdot\text{mm}}{1.214 \times 10^4 \text{ mm}^3} = 0.708 \text{ MPa}$$

The ratio is

$$\frac{\sigma_{max,N}}{\sigma_{max,P}} = 2.81$$

so the load normal to the web orientation produces about 2.8 times the bending stress of the load parallel to the web orientation. For a simply supported beam with a central point load, the maximum deflection is given as

$$\delta_{max} = \frac{FL^3}{48EI}$$

Using $E = 3500N/mm^2$ PLA^[2]. The load parallel to the web:

$$\delta_{parallel} = \frac{(137.5N)(250mm)^3}{48(3500N/mm^2)(1.194 \times 10^6 mm^4)} = 1.071 \times 10^{-2} mm$$

Load normal to the web:

$$\delta_{normal} = \frac{(137.5N)(250mm)^3}{48(3500N/mm^2)(3.642 \times 10^5 mm^4)} = 3.511 \times 10^{-2} mm$$

Therefore,

$$\frac{\delta_{normal}}{\delta_{parallel}} = 3.28$$

This confirms that the load normal to the web case is also much more demanding from a stiffness perspective.

- Web Shear Stress at the Fracture Section

The splice connection must transfer the internal shear force at the fractured section. From beam equilibrium,

$$V_{fracture} = 137.5 N$$

This same section shear force must be transferred across the splice in both loading orientations. However, the section shear stress distribution changes between orientations because the first moment of area Q , the second moment of area I , and local breadth b in the shear stress formula

$$\tau = \frac{VQ}{Ib}$$

depend on the bending axis and on the location where shear stress is evaluated.

- Load Parallel to the web: strong-axis shear estimate

When the load acts parallel to the web, the beam bends about the centroidal x-axis. Therefore,

$$I = I_x = 1.194 \times 10^6 mm^4$$

For the conventional strong-axis web-shear estimate, the shear stress is evaluated at the neutral axis in the web. The area above the neutral axis includes the top flange and the upper half of the web:

$$A_f = b_f t_f = (60mm)(10mm) = 600 mm^2$$

$$A_{w/2} = t_w \frac{h_w}{2} = (10mm)(25mm) = 250 \text{ mm}^2$$

The centroid distances from the neutral axis are

$$\bar{y}_f = \frac{h_w}{2} + \frac{t_f}{2} = 25mm + 5mm = 30 \text{ mm}$$

$$\bar{y}_{w/2} = \frac{h_w}{4} = 12.5 \text{ mm}$$

Thus,

$$Q_x = A_f \bar{y}_f + A_{w/2} \bar{y}_{w/2} = 21125 \text{ mm}^3$$

At the neutral axis, the local breadth is the web thickness:

$$b = t_w = 10 \text{ mm}$$

Therefore,

$$\tau_{parallel} = \frac{V_f Q_x}{I_x t_w} = \frac{(137.5N)(21125mm^3)}{(1.194 \times 10^6 mm^4)(10mm)} = 0.708 \text{ MPa}$$

- Load normal to the web: weak-axis shear estimate

When the load acts normal to the web, the beam bends about the centroidal y-axis. Therefore,

$$I_y = 3.642 \times 10^5 \text{ mm}^4$$

For this orientation, the first moment of area is taken about the y-axis. A representative estimate can be made by evaluating shear stress at the vertical centroidal axis using the area on one side of the axis.

The right half of each flange has an area

$$A_{f, right} = \frac{b_f}{2} t_f = (30mm)(10mm) = 300 \text{ mm}^2$$

with centroid distance $\bar{x}_f = 15 \text{ mm}$. Since there are two flanges,

$$Q_{y, flanges} = (2)(300mm^2)(15mm) = 9000 \text{ mm}^3$$

The right half of the web has an area,

$$A_{w, right} = \frac{t_w}{2} h_w = (5mm)(50mm) = 250 \text{ mm}^2$$

with centroid distance $\bar{x}_w = 2.5 \text{ mm}$. So,

$$Q_{y,web} = (250mm^2)(2.5mm) = 625 mm^3$$

Thus,

$$Q_y = Q_{y,flanges} + Q_{y,web} = 9000 mm^3 + 625 mm^3 = 9625 mm^3$$

At the vertical centroidal axis, the local breadth of the intact I-section is the total section depth:

$$b = h = 70 mm$$

Thus,

$$\tau_{normal} = \frac{V_f Q_y}{I_y h} = \frac{(137.5N)(9625mm^3)}{(3.642 \times 10^5 mm^4)(70mm)} = 0.0519 MPa$$

This value is an intact beam section weak-axis shear estimate only. It should not be interpreted as a direct contact stress in the splice plate. Although the section shear stress can be estimated using the shear stress formula, the repaired connection does not transfer load through a continuous bonded plate area. The splice is bolted, so the force transfer occurs primarily through the discrete bolt locations. Therefore, the most important splice-level shear quantity is still the fracture section shear force $V_{fracture} = 137.5N$, which is distributed among the bolts.

In the load normal to web orientation, the external load direction is also normal to the splice plate faces. This may create additional local plate bending, contact pressure, and deformation near the loading and bolt hole regions. These local effects are not accurately accounted for by a hand calculation of shear area. Instead, they are better evaluated through the finite element analysis, where stress concentration near the bolt holes and splice faces can be observed directly.

- Simplified Splice Load-Transfer Model

The fracture interrupts the continuity of the I-beam at the section of maximum moment. The splice must therefore transfer load between the two beam halves through the web region. A simplified model is adopted here in which the bolts transfer the fracture section shear through the web, while the splice plates bridge the fracture and distribute this transfer over a length l_p . Since the flanges are not directly spliced, but through bolted joints, the repair is not expected to fully reproduce the stiffness of the intact beam. Therefore,

$$\delta_{repaired} > \delta_{intact} \quad \text{and} \quad k_{repaired} < k_{intact}$$

where k is the effective beam stiffness:

$$k = \frac{F}{\delta}$$

The connection must therefore provide both force transfer and rotational restraint at the fractured section.

- Bolt Group Geometry

The bolts resist both the direct shear across the fracture and the rotation tendency of the two beam halves. The direct shear per bolt is estimated as

$$V' = \frac{V_f}{n}$$

and the moment-induced secondary shear follows the bolt-group relation

$$V_i'' = \frac{M_b r_i}{J_b}, J_b = \sum r_i^2$$

where r_i is the distance from the bolt-group centroid to each bolt. A larger J_b reduces the secondary shear caused by a given moment M_b . For the four-bolt case, the bolts are at $(\pm 12, \pm 10) \text{ mm}$:

$$J_{b1} = 4(12^2 + 10^2) = 976 \text{ mm}^2$$

$$V_1' = \frac{137.5}{4} = 34.38 \text{ N}$$

For the 6 bolts case, the bolts are at $(\pm 16, 14)$, $(\pm 16, 0)$, and $(\pm 16, -14) \text{ mm}$:

$$J_{b2} = 4(16^2 + 14^2) + 2(16^2) = 2320 \text{ mm}^2$$

$$V_2' = \frac{137.5}{6} = 22.92 \text{ N}$$

$$\frac{J_{b2}}{J_{b1}} = 2.38$$

Therefore, the 6 bolts design has a larger bolt-group polar measure and a lower direct shear per bolt, so it is expected to reduce the maximum resultant bolt demand.

- Bolt Shear and Bearing Checks

Bolt shear stress is estimated by

$$\tau_b = \frac{F_b}{A_b}, F_b = \frac{V_f}{n}, A_b = \frac{\pi d^2}{4}$$

and bolt under shear relation using the von Mises shear-yield form gives

$$n_{shear} = \frac{S_y^{bolt}}{\sqrt{3}\tau_b}$$

where S_y^{bolt} is the bolt yield strength. The member bearing factor of safety is

$$n_{bearing, member} = \frac{S_y^{member}}{\frac{F_b}{dt}}$$

For this analysis,

$$S_y^{bolt} = 215MPa \text{ (for stainless steel bolts)}$$

$$S_y^{member} = 36MPa \text{ (for PLA beam and splice material)}$$

Table 1: Calculated bolt group parameters

Quantity	M3 x 4 Bolt Group	M5 x 6 Bolt Group
F_b	34.38 N	22.92 N
$\tau_b = F_b/A_b$	4.86 MPa	1.17 MPa
n_{shear}	24.3	101.2
Web $\frac{F_b}{dt}$	1.15 MPa	0.458 MPa
$n_{bearing, web}$	31.4	78.6
Splice $\frac{F_b}{dt}$	2.86 MPa	0.764 MPa
$n_{bearing, plate}$	12.6	47.1

6-bolt design gives lower bolt shear stress and lower bearing stress because it uses more bolts, larger bolt diameter, and thicker splice plates.

- Stress Concentration

The bolt holes interrupt the load path and reduce the local load-carrying area, so stress concentration is expected near the hole boundaries. A general way to describe local stress amplification is

$$\sigma_{max} \approx K_t \sigma_{nominal}$$

where K_t depends on hole geometry, spacing, edge distance, and contact condition. Since this splice has multiple bolt holes and contact-based load transfer, a single determinant K_t value is not used. Instead, the analytical model identifies the expected high-stress region, while FEA is used to evaluate the actual local von Mises stress concentration.

Computational Investigation

Finite element analysis was performed in SolidWorks for four repaired-beam cases: 4-bolt and 6-bolt splice designs under load parallel to the web and load normal to the web. Intact beam models were also analyzed in both orientations to provide stiffness baselines. The applied load was kept constant at $F = 275 \text{ N}$ for all simulations. The beam and splice plates were modeled with a custom PLA-like material:

$$E = 3500 \text{ N/mm}^2, \nu = 0.36, \rho = 1300 \text{ kg/m}^3, S_y = 36 \text{ MPa}$$

The bolts and nuts were modeled using SolidWorks bolted connection features. M3 bolts were used for the 4-bolt design, and M5 bolts were used for the 6-bolt design. The bolt material was assumed to be AISI 316 stainless steel, and an axial preload of 200 N was applied to each bolted joint. The boundary conditions matched the analytical model: supports were placed near both ends to approximate a simply supported beam, and the load was applied at midspan. The load parallel to the web case corresponds to strong-axis bending, while the load normal to the web case corresponds to weak-axis bending.

- Mesh Convergence

A blended curvature-based solid mesh with high-quality elements was used. Mesh convergence was evaluated using the percent change in maximum von Mises stress:

$$\left| \frac{\sigma_i - \sigma_{i-1}}{\sigma_{i-1}} \right| < 0.05$$

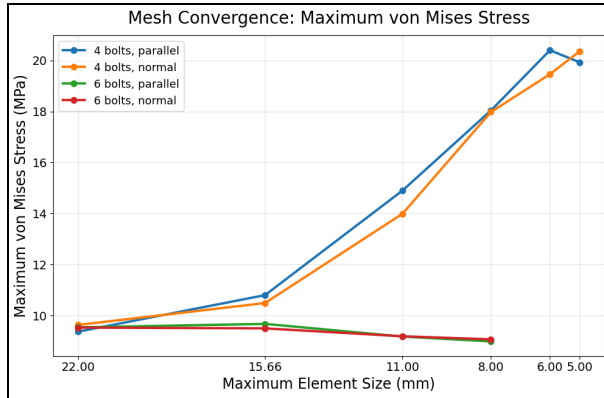


Figure 5(a): Max stress vs. Max Mesh Size

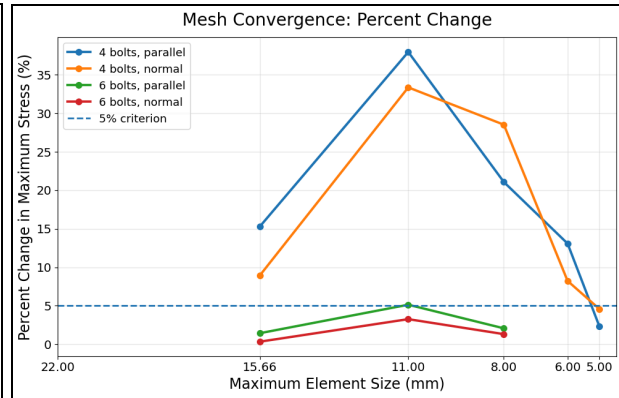
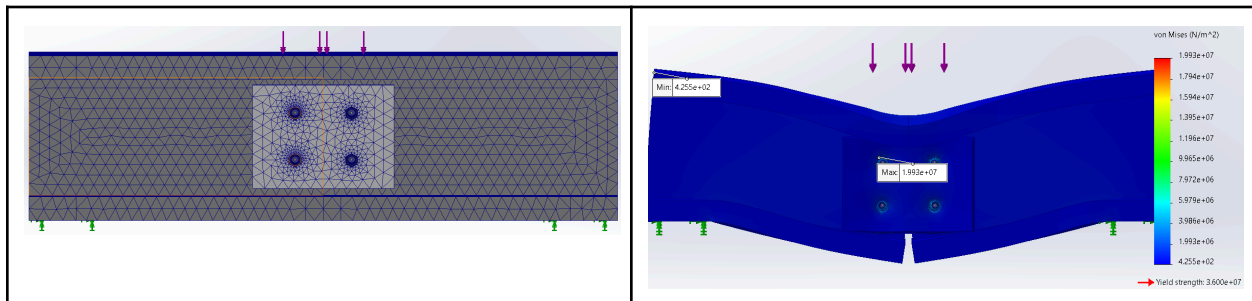


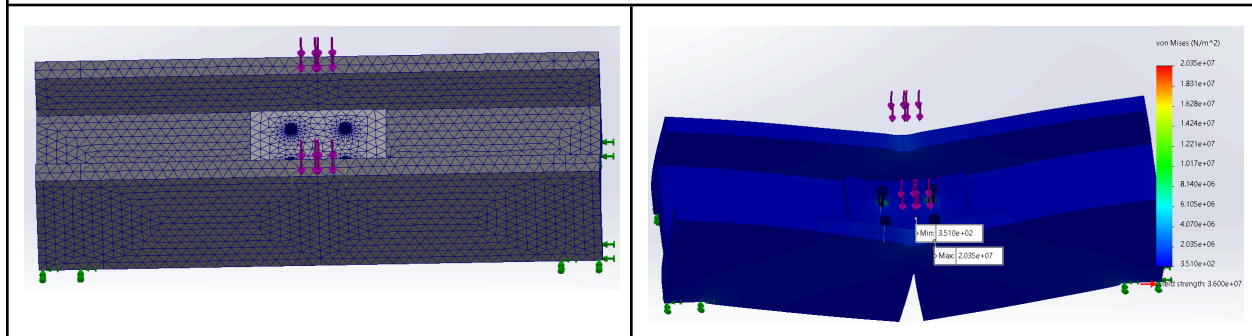
Figure 5(b): % change vs. Max Mesh Size

The 6-bolt cases converged at a maximum element size of 8 mm, while the 4-bolt cases required refinement to 5 mm. The final percent changes were 2.30%, 4.57%, 2.07%, and 1.32% for the 4-bolt parallel, 4-bolt normal, 6-bolt parallel, 6-bolt normal cases, respectively. Since all were below 5%, the meshes were considered sufficiently converged.

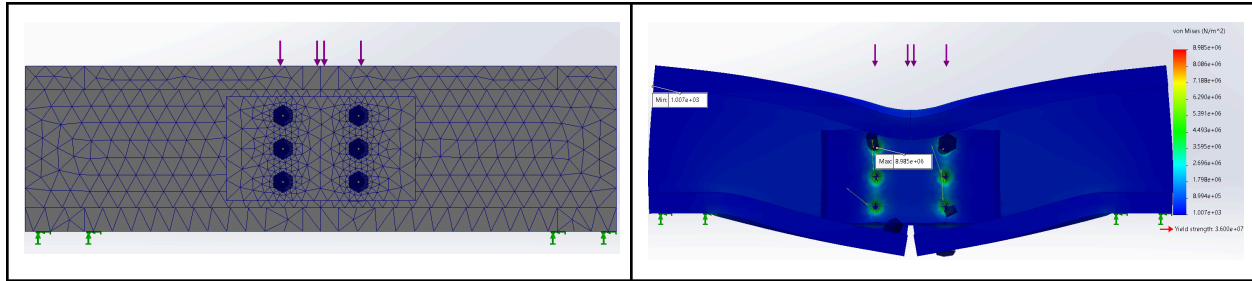
- FEA Results



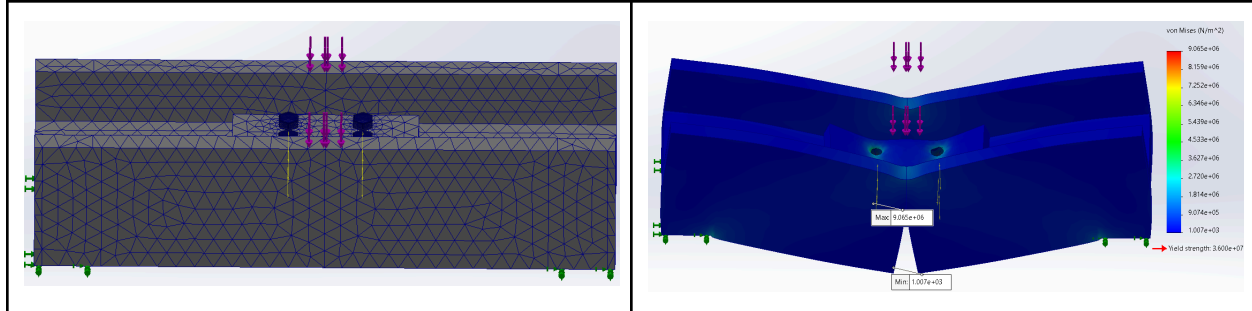
4-Bolt Load Parallel to Web: Mesh and Von Mises Stress Result



4-Bolt Load Normal to Web: Mesh and Von Mises Stress Result



6-Bolt Load Parallel to Web: Mesh and Von Mises Stress Result



6-Bolt Load Normal to Web: Mesh and Von Mises Stress Result

The effective stiffness was calculated as

$$k_{eff} = \frac{F}{\delta}$$

where δ is the maximum displacement in the loading direction.

Table 2: FEA stress, displacement, and stiffness results for intact and bolted beams

Model	Orientation	Max Stress (MPa)	Stress Location	Max Disp. (mm)	Stiffness (N/mm)
Intact	Parallel	0.923	Top middle	0.02957	9299.9
Intact	Normal	2.041	Support-edge transition	0.03511	7832.5
4 x M3	Parallel	19.93	Bolt hole	0.03134	8774.7
4 x M3	Normal	20.35	Bolt hole	0.04797	5732.7
6 x M5	Parallel	8.985	Bolt hole	0.03097	8879.6
6 x M5	Normal	9.065	Bolt hole	0.04062	6770.1

The stress plots show that most of the beam and splice plates remain in the low-stress range, while the maximum stresses occur locally near the bolt holes. This agrees with the analytical expectation that bolt holes create stress concentrations due to discrete bearing/contact load transfer. Elevated stresses near the supports are treated as boundary-condition effects rather than

the primary splice design concern. The 6-bolt M5 design produced much lower maximum stress than the 4-bolt M3 design. In the parallel case, stress decreased from 19.93 MPa to 8.985 MPa. In the normal case, stress decreased from 20.35 MPa to 9.065 MPa. This supports the analytical prediction that more bolts, larger bolt diameter, and a larger bolt-group spread improve load distribution.

- Stiffness Recovery

Stiffness recovery was calculated using

$$\text{Stiffness recovery} = \frac{k_{\text{repaired}}}{k_{\text{intact}}} \times 100\%$$

Table 3: Percentage of stiffness recovery for each design case

Repaired Case	Compared Intact Case	Stiffness Recovery
4 x M3, Parallel	Intact, Parallel	94.4%
4 x M3, Normal	Intact, Normal	73.2%
6 x M5, Parallel	Intact, Parallel	95.5%
6 x M5, Normal	Intact, Normal	86.4%

Both designs recovered most of the intact stiffness in the load parallel to the web case. The normal to the web case was more demanding because it bends about the weaker axis. In that orientation, the 6-bolt design improved stiffness recovery from 73.2% to 86.4%. Overall, the FEA results show that the 6-bolt M5 splice provides better structural performance. It lowers bolt-hole stress concentration, improves stiffness recovery, and distributes load more effectively across the splice region.

Experimental Investigation

- Objective

The purpose of the experimental investigation is to determine the deflection due to applied load conditions. The two designs are experimented upon, allowing for a comparison of the overall stiffness and performance of the two designs. Experimental results are then compared to FEA predictions.

- Fabrication

All of our specimens were manufactured via FDM 3D printing with PLA filament. Parts were sliced using a 0.20 mm standard profile, corresponding to 0.20 mm layer height, 15% infill, and other default parameters for PLA.

The I-beam halves were printed standing on their flat faces, with each half's long axis oriented vertically on the print bed. In this orientation, the layer lines lie in planes perpendicular to the beam's longitudinal axis. This is an important distinction in our setup, as bending stresses developed during testing will act directly across the layer interfaces. We recognize this to be the weakest orientation for the loading applied in our experiment, since FDM printed parts exhibit much lower strength and stiffness across layer lines. This printing orientation was chosen out of fabrication convenience by removing the need for support material. The splice plates, which are loaded primarily in shear and bearing rather than bending across their thickness, were printed flat on the bed so that their layer lines lie in the plane of the plate and are not oriented unfavorably with respect to the loading condition. The bolts used to assemble the splice connections were steel, button-head fasteners. Design 1 was assembled using four M3 bolts, and Design 2 was assembled using six M5 bolts.

- Test Framework

The structure of our tests is summarized in Table 1.

Table 4: Test framework for experimental setup

Test #	Specimen	Loading Orientation	Bending axis
1	Design 1	to web	I_x (Strong)
2	Design 1	⊥ to web	I_y (Weak)
3	Design 2	to web	I_x (Strong)
4	Design 2	⊥ to web	I_y (Weak)

- Test Procedure

Each design was assembled with its corresponding splice plates and bolts and placed across two rigid supports separated by a clear span of 250 mm. Both supports were positioned at equal heights so that the beam was level before loading. A cord was tied around the beam at its midspan to serve as the load attachment point, with the weights tied onto the cord in succession. Figure 6 shows the experimental setup during a representative trial of Design 2 loaded (24 kg, 235 N) parallel to the web.



Figure 6: Design 2, loaded parallel to web



Figure 7: Midspan deflection of D2, loaded parallel to web

Midspan deflections were measured by holding a rigid straightedge across the top of a supported end to the midspan, where digital calipers were used to measure from the top of the straightedge to the face of the beam. The reference reading was recorded with no load prior to each test, and the deflection at each subsequent load step was computed as the increase in this distance relative to the no-load reading. This measurement method is demonstrated in Figure 7.

Initial testing of Design 1 (37N) proved to be too small of a force to produce a measurable deflection. The corresponding deflection readings were within ± 0.1 mm of the no-load value across the entire bucket's weight range. This setup is demonstrated in Figure 8.

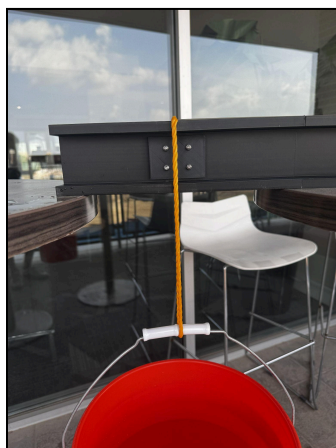


Figure 8: Design 1 in water-based setup, loaded parallel to web

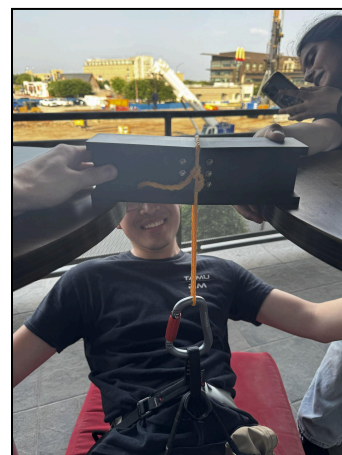


Figure 9: Team member suspended from Design 2, parallel loading

We determined that changing our loading approach would be necessary for the accuracy of our data collection, and it was therefore modified to discrete metal weights. The final loading method used three discrete weight steps of 20 kg, 24 kg, and 28kg, corresponding to applied forces of 196.2 N, 235.4 N, and 272.7 N, respectively. At each step, the load was applied and allowed to stabilize before the deflection reading was taken as outlined above.

Even at the largest discrete weight of 28 kg, the midspan deflections remained around 2-2.5 mm with no visible damage to any part of the design. It became apparent that bringing the beam to failure was not possible, given the weights we had access to, as the structure was substantially stiffer and stronger than the weights could exploit. To investigate the upper bound of the beam's load capacity, the heaviest available load was tested: a team member with a mass of approximately 85 kg (or 834 N) was suspended from the midspan in place of the weights, as seen in Figure 9. This loading produced the largest deflection of the given beam, but still showed no visible damage. The only observable effect of this loading was the indentation of the cord into the plastic at the top edges of the beam.

After testing, the splice regions were more closely inspected for any signs of damage. The bolts were loosened and the splice plates removed. No visible elongation of any bolt hole in the bearing direction was found, no plastic deformation of the splice plates was found, and no cracking or general surface damage along the web or flanges of the I beam was found. The absence of damage at this highest 834 N case means that this load can only be reported as a lower bound, where no damage was observed up to approximately 834 N.

Table 5: Recorded deflections for each loading & orientation case

Mass (kg)	Load (N)	D1 to web (mm)	D1 $\perp$ to web (mm)	D2 to web (mm)	D2 $\perp$ to web (mm)
20	196.2	1.8	2.1	1.4	1.9
24	235.4	2.2	2.6	2.0	2.2
28	274.7	2.4	2.7	2.2	2.4
~85	~833.8	-	-	~3.0	-

- Limitations

There were several aspects of the experimental setup that limited the precision of our results and should be considered when comparing them to the analytical and computational results.

Our method of measuring deflection was valid enough to produce the expected responses of the relative deflections of each beam. Meaning D1 and D2's deflections in normal loading were

greater than their parallel loading configuration, and all D2 deflections were less than all D1 deflections for a given load; this can be seen in Table 5. However, the precision of our deflection measurements was low, and the high stiffness of the beams produced minor differences in deflection between loads, which means our data is not as reliable as if we had made a less stiff (i.e., more measurable) beam.

Additionally, the beams were oriented on the print bed with their long axis vertical, in which the layer lines are perpendicular to the bending stress under load. We recognize this as the weakest printing orientation for this experiment, and it is expected to reduce stiffness and the failure load compared to layer lines parallel to the beam axis. While this didn't prevent the beam from carrying our highest loads, it can contribute to differences between experimental deflections and the analytical/computational predictions made using published PLA material properties. To further this point, infill percentage, printing inconsistencies, accumulated material wear between tests, and variation in loading location all additionally contribute to widening the gap between our experimental data and analytical/computational predictions.

Results and Discussion

The two splice repair designs were compared using analytical calculations, finite element analysis, and experimental testing. Overall, all three approaches showed the same trends: loading normal to the web produced larger deflections and greater repair demand than loading parallel to the web, and Design 2 performed better than Design 1. This agrees with the analytical results, since the I-beam has a lower second moment of area in the weak-axis orientation.

The analytical calculations showed that the splice must transfer shear across the fractured midspan section while also limiting relative rotation between the two beam halves. Design 2 uses six M5 bolts rather than four M3 bolts, so the direct shear per bolt is lower. Its larger bolt diameter, larger bolt-group spread, and thicker splice plates also reduce bearing stress and improve load sharing. Therefore, Design 2 was expected to produce lower local stresses and better stiffness recovery.

The FEA results confirmed this expectation. In all repaired-beam models, the maximum von Mises stress occurred near the bolt holes, implying that the splice region governs the local stress response. Design 1 produced maximum stresses of 19.93 MPa for load parallel to the web and 20.35 MPa for load normal to the web. Design 2 reduced these stresses to 8.985 MPa and 9.065 MPa, respectively. This reduction shows that the larger and more distributed bolt pattern in Design 2 transferred load more effectively and reduced stress concentration around individual holes.

The stiffness results also favored Design 2. In the load-parallel-to-web case, both repairs recovered most of the intact beam stiffness, with Design 1 recovering 94.4% and Design 2 recovering 95.5%. In the load-normal-to-web case, the difference was more significant: Design 1 recovered 73.2% of the intact stiffness, while Design 2 recovered 86.4%. This shows that the larger splice design is especially beneficial in the weaker bending orientation.

The experimental results followed the same general pattern. For every controlled load and orientation tested, Design 2 had lower deflection than Design 1, and both designs deflected more when loaded normal to the web. At 274.7 N, Design 1 deflected 2.4 mm parallel to the web and 2.7 mm normal to the web, while Design 2 deflected 2.2 mm and 2.4 mm, respectively. No visible damage was observed in the splice plates, bolt holes, web, or flanges. Since Design 2 also survived an approximate 833.8 N load without visible failure, this load can only be reported as a lower bound for its capacity.

The experimental deflections were larger than the FEA deflections, which is likely due to differences between the idealized model and the physical specimens. The FEA assumed ideal material properties, boundary conditions, and bolt behavior, while the specimens were 3D printed PLA with 15% infill and anisotropic layer behavior. Measurement uncertainty, support contact, bolt tightening, and loading location may also have affected the experimental data. Therefore, the experimental results are most useful for comparing the relative performance of the two designs rather than matching the exact FEA deflections.

Overall, Design 2 is the better repair configuration. It reduced bolt-hole stress concentration, improved stiffness recovery, lowered the load carried by each bolt, and produced smaller experimental deflections. Design 1 was still able to carry the applied loads without visible damage, but its higher stress and lower stiffness recovery make it less effective than Design 2.

Conclusions

Two bolted splice designs were developed and evaluated for repairing a fractured I-beam. The designs were compared using analytical calculations, finite element analysis, and experimental testing. Across all three approaches, loading normal to the web produced greater deflection and higher stress than loading parallel to the web because of the lower second moment of area in the weak-axis orientation. Both designs were able to carry the experimental loads without visible damage, but Design 2 consistently provided better performance. Its thicker and longer splice plates, larger bolts, and six-bolt layout reduced local stress concentration, improved load sharing, and increased stiffness recovery compared with Design 1. Based on these results, Design 2 is the more effective splice repair configuration for restoring strength and stiffness in the fractured I-beam.

References

- ^[1] Hossain, Z., “MEEN 368 Project: Design of a Bolted Splice Repair for a Broken I-Beam.”
- ^[2] Farah, S., Anderson, D. G., and Langer, R., “Physical and mechanical properties of PLA, and their functions in widespread applications — a comprehensive review - sciencedirect,” ScienceDirect [Online]. Available: <https://www.sciencedirect.com/science/article/abs/pii/S0169409X16302058>.