Behavior of Spliced Steel Girders under Static Loading

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ABSTRACT

In this paper, the behavior of spliced steel girders under static loading is investigated. A group of seven steel I-girders were tested experimentally. Two concentrated loads were applied to each specimen at third points and the load was increased incrementally up to the yield of the specimen. Two types of splices were considered; the bearing type and the friction-grip type splices. For comparison, an analytical study was made for the tested girders in which the finite element analysis program (Abaqus) was used for analysis. It was found that the maximum test load for spliced girders with bearing type splices was in the range of (34%) to (67%) of the maximum test load for the reference girder. For girders spliced by using friction-grip type splices, the maximum test load was in the range of (90%) to (99%) of the maximum test load for the reference girder. The analytical results show a good agreement with the experimental results with a difference in maximum deflection at midspan was not more than (15%) at maximum load for all girders.

Key words: bolted splices, bearing type splices, friction-grip type splices, finite element modeling.

تصرف الروافد الفولاذية الموصولة تحت تاثير الحمل الساكن

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الخلاصة

في هذا البحث تم دراسة سلوك الروافد الفولاذية ذات الوصلات تحت تأثير الأحمال الإستاتيكية. تم إجراء فحص مختبري لمجموعة مكونة من سبعة روافد(رافدة مرجعية و ستة روافد ذات وصلات). تم تسليط قوتين مركزتين في نقاط الثلث لكل نموذج على مراحل حتى الوصول الى حمل الخضوع. لأغراض المقارنة, تم إجراء دراسة تحليلية للنماذج التي تم فحصها بإستخدام برنامج العناصر المحددة (Abaqus). من خلال النتائج المختبرية التي تم الحصول عليها وجد ان الحمل الأقصى للنماذج ذات الوصلات من نوع تحميل (Bearing Type Splices) يتراوح بين(34%) و (67%) من الحمل الأقصى للرافدة المرجعية. أما بالنسبة للروافد ذات الوصلات من نوع إحتكاك(Friction-grip Type Splices), فقد كان الحمل الأقصى يتراوح بين (90%) و(99%) من الحمل الأقصى للرافدة المرجعية. تم الحصول على توافق جيد بين النتائج التحليلية والمختبرية حيث كان الفرق في الإنحراف لايتجاوز (15%) عند الحمل الأقصى.

1. INTRODUCTION

Rolled beams or plate girders are often spliced for several reasons, such as: (a) the required full length of beam or girder may be greater than the standard length, (b) to overcome length limitations of structural components as a result of fabrication, and transportation facilities, and (c) the design may require a change in the cross section of the beam. **Fig. 1** shows a typical bolted splice in a steel girder.

Splices in beams and girders are generally classified into two types:1)Shop splices and 2) Field splices. Shop splices are made during the fabrication of the member in the shop. They are usually used when the length of a structural component forming a beam or a girder is limited by the fabrication or handling process available. Field splices are necessary when a steel girder becomes too long to be transported in one piece from the shop to the construction site. Two types of bolted splices are commonly in use for girders and they are as follows: (a) web-flange splices which is the more commonly used and (b) end-plate splices. Both types are shown in **Fig. 2**. The main difference between these two types of splices is the type of forces to which the bolts are subjected. The bolts in the web- flange splices are subjected to shear forces only, whereas the bolts in the end- plate splices are subjected to combined axial and shear forces.

At present, different design procedures are followed for web- flange splices. For example, **Fuisher,** and **Struik,1974** assumed that the web splice transfer all the shear force and the flange splice must resist the force (M/d). The bolts in the web splice are assumed to be designed for the eccentric shear force (v) with an eccentricity (e) equal to the distance between the centroid of the fastener group on each side of the splice (see **Fig. 3)**

The **AISC,2005** specifications require that bolted beam or girder splices should be designed to resist the most unfavorable combination of shear and moment at the location of splice. However, it does not provide insight into how the eccentric effect of the shear force should be accounted for in the design of a web splice or how the moment at the section should be proportioned between web splice and the flange splices

The **BS-5950, 1987** specifications recommend that the splices in beams should be designed to transmit all the forces and moments in the member at that point and have adequate stiffness. The **AASHTO**, **2002** specifications require that the web splices be designed for the shear force, moment due to the eccentricity of the shear force, and the portion of the design moment resisted by the web. Flange splices according to **AASHTO**, **2002** specifications should be designed for the moment portion not resisted by the web. Based on one of the previous design methods and depending on the required joint (splice) performance, friction- type as well as bearing type joint splices can be used

2. EXPERIMENTAL PROGRAM

Each test specimen was placed in a test rig and simply supported as shown in **Fig. 4**. The load was applied by a hydraulic jack with (115 kN) capacity and distributed equally by a rigid steel beam to the specimen third points. Seven test specimens (one intact girder and the others were spliced at different locations) were manufactured and used in the experimental investigation. Each test specimen has a total length of (2.453 m) and a clear span of (2.403m). The cross-section dimensions and the details of splice for the test girders are given in **Fig. 5**. The independent variables for the test specimens are: a) location of splice, b) connection type for the splice, and c) number of splices along the girder span. The splices were designed according to **AASHTO**, **2002** specifications. M10 grade 8.8 high strength bolts were used for both types of splices for all spliced steel girders used in the experimental program. The bolt holes were drilled with a diameter of (11mm). Washers were used under both the bolt head and nut. The bolts were installed in accordance to the specifications of **RCSC, 2004** Research Council on Structural Splices) for structural joints using high strength bolts.

In bearing type connection, the bolts were tightened to the snug-tight condition to bring the connection plies into firm contact. . Ordinary spanner was used to attain the snug-tight condition. The axial bolt strain caused by the snug-tight condition was measured and it was found to be in the range [467-500] (micro strain).

In friction type splices, the bolts were torqued (by using a digital torque meter) until the minimum required pretension force was reached. The minimum required pretension is equal to (70%) of the specified minimum tensile strength as specified by **RCSC, 2004.** For each bolt, the torque was applied by a digital torque-meter (**Snap-On** model, made in USA) and the resulting axial strain in the bolt was measured by using the **KFG-2N-120-C1-11L12MR** (made in Japan for **Omega Engineering**) type strain gage which was bonded to the non-threaded part of the bolt shank. The pre-wired strain gage was (2mm) gage length, (120Ω) resistance, (2.1) gage factor and it was bonded to the bolt surface by using **SG401** instance adhesive which was specially used for the strain gage type. It was found that the required torque for flange bolts was (97 N.m) to reach the minimum required pretension force. For web bolts, the required torque was (86 N.m). For each specimen, the load was applied incrementally up to the maximum load which is equal to or greater than the yield load of the girder ($P_{max} \geq P_y$). The maximum load (Pmax) was assumed to be reached when the girder deflection was increasing in a non-proportional way with load. Details of the test specimen are shown in **Fig. 6.**

3. TEST RESULTS AND DISCUSSION

The test results are given in **Table 1** and **Figs. 7** to **12** show the load-deflection curves for the girders. The splice locations are as stated below each figure. It can be seen from the results that the maximum load for the spliced girders (G1bs (mid), G2bs (third)) is less than (55% P_{max}) for the reference girder (RGs). This is attitude to the small clamping force between the connected plies for bearing type connection used in the girders, and also due to the existence of (1mm) gap between the bolt shank and the hole, and the location of the splice. Hence, a relatively smaller applied load is enough to cause sliding between the connected plies and consequently the load-deflection curve is to be diverge from that of the reference girder. **Fig. 7** shows that when (26.63%) of the maximum applied load for the reference girder was applied to the spliced girder (G1bs(mid)), the midspan deflection will be equal to the deflection of the reference girder at maximum load. This ratio was found to be (26.47%) for (G2bs (third)) (**Fig. 9**) and (49%) for (G1bs(third)) (**Fig. 8**).

For girders (G1fs (mid), G1fs (third) and G2fs (third)) the load-deflection curves for both midspan and third point are identical with those for reference girder to a large extent up to a load ratios equal to (69.38%, 68.44% and 71.76%) (of max applied load for reference girder (RGs)) for the three girders respectively. It is clear that the deflection of spliced steel girders using the friction-grip type splices is almost identical to that of the reference girder at a load ratio that produces the allowable bending stress state (i.e. $P_{allw.}$=0.55P_y) or (σ_{all}=0.55σ_y)as specified by **AASHTO**, **2002** specifications. In other words, the load-deflections curves for girders spliced by using friction-grip type splices are identical to that of the reference girder up to a load greater than that required to produce the allowable bending stress in the reference girder.

4. ANALYTICAL APPROACH

A three-dimensional finite element model for a spliced steel girder was developed in order to analyze the girders under static loads. Because of complexity of the model simulation, the starting point for the model was a simple plate with a bolt bearing against a hole .The model was then developed to form a single lap joint. Finally, the real spliced steel girder including the I-girder, cover plates and bolts were assembled and modeled as shown in **Fig. 13**which is a model example. All the parts of the model were modeled using the 8-node continuum three dimensional brick element (C3D8R) with reduced order integration available in **Abaqus.** This element has the capability of representing large deformation, geometric and material non-linearities.

The surface -to-surface contact with small sliding was considered for all the contact interactions in the model which assumed relatively small sliding, but could undergo arbitrary rotation of the bodies. The master surfaces in the contact pairs represent the bolt shank, girder flange, girder web, and the surfaces of the cover plates contacting the bolt head and the nut, whereas the surfaces interacting the master surfaces were considered as slave surfaces. The tangential contact interaction between the bolt head-(flanges/web) cover plates, nut-(flanges/web) cover plates, and (flanges/web) cover plates-(girder flanges/girder web) was modeled by using penalty friction formulation with mean friction coefficient of (0.3),**Kulak, et al, 2001.**

5. NUMERICAL ANALYSIS RESULTS

The Load versus deflection curves obtained from the finite element analysis are presented and compared with the experimental load-deflection curves as shown in **Figs. (18 -24)**. In general, it can be noted from the plots that the finite element results are close to the experimental test results throughout the entire range of behavior . The summary of comparison between the numerical and experimental results is presented in **Table 2**. It can be seen that the (num./ exp.) deflection ratios at the maximum test load for the girders are in the ranges of (0.88-1.15) and (0.88-1.09) at midspan and third point respectively. This variation in results is mainly attributed to the nonlinear behavior of the splice which depends on several variables such as: contact conditions between the splice components; variation of pretension forces in the bolts and coefficient of friction between the splice components which cannot be modeled exactly by any numerical analysis technique.

6. CONCLUSIONS

1. For girders having bearing type splices at midspan, or at third point or at two third points, the maximum test loads were (43.53%), (67.06%), and (34.12%) of that for the reference girder respectively. Also, it was found that the maximum load for the same girders spliced by using friction- grip type splices was (98.82%),(99.76%), and (90.58%) of that for the reference girder. This indicates the importance of using friction-grip type splices.
2. It was found that when (26.63%) of the maximum test load for the reference girder was applied to the girder having bearing type splice at midspan, the resulting midspan deflection will be equal to the midspan deflection of the reference girder at maximum test load. This ratio was found to be (49%) and (26.47%) for girders having bearing type splice at third point or at two third points respectively.
3. For girders having friction-grip type splices at midspan, or at third point or at two third points, it was found that the load-deflection curves were almost identical with that for the reference girder up to a load equal to (69.38%), (68.44%), and (71.76%) of the maximum test load for the reference girder respectively.

4. The results obtained by using the finite element analysis method using **Abaqus.** were found to be in a very good agreement with the experimental results with a difference in maximum deflection at yield load not more than (15%) for all the tested girders.
5. From the FE analysis, it was found that the moment carried by the web splice plates for girders spliced by using bearing type splices was found to be (0.365) to (0.431) times the total moment at splice centerline up to the elastic load level. At maximum test load, this moment ratio was found to be (0.312) to (0.487).
For girders spliced by using friction-grip type splices, the ratio of the moment carried by the web splice plates was (0.09) to (0.21) times the total moment at elastic range. At maximum test load, this moment ratio was (0.20) to (0.22) of the total moment.
6. From the FE analysis, it was found that the shear force carried by the web splice plates at elastic range was (0.369) to (0.385) times the total shear at splice centerline for girders spliced by using bearing type splices. At maximum test load, this shear value was (0.101) to (0.123) times the total shear.

For girders spliced by using friction-grip type splices, the ratio of shear force carried by the web splice plates was (0.386) to (0.410) times the total shear at elastic range. At maximum test load, this shear force was (0.279) to (0.298) times the total shear.

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Table 1. Static test results.

Specimen	Splice Condition	Max Load $P=P_{max}$ (kN)	Midspan Deflection Δ(mm)	Third Point Deflection Δ (mm)	Midspan Def. at Load (P=22.46 kN)(**)		Third Point Def. at a Load (0.55 P_{max}) of(RGs)	
RGs	No Splice	40.85	16.69	14.20	8.58	1.0(*)	7.67	1.0(*)
G1bs(mid)	One Splice at Midspan (Bearing Type Splices)	17.78	22.78	16.84	–	–	–	–
G1bs(third)	One Splice at Third Point (Bearing Type Splices)	27.39	23.60	23.26(*)	19.52	2.275	23.20	3.025
G2bs(third)	Two Splice at Third Points (Bearing Type Splices)	13.94	28.55	27.57	–	–	–	–
G1fs(mid)	One Splice at Midspan (Friction Type Splices)	40.37	26.80	21.38	8.73	1.018	7.90	1.030
G1fs(third)	One Splice at Third Point (Friction Type Splices)	40.75	22.82	22.86	8.76	1.021	8.00	1.043
G2fs(third)	Two Splice at Third Points (Friction Type Splices)	37.00	25.75	26.07	8.28	0.965	7.45	0.971

(*) ratio of deflection value to that of reference girder(RGs)
(*) this value is at a load of (P=22.59 kN)
(**) which represents (0.55 P_{max})of the reference girder (RGs)

Table 2. Comparison between experimental and numerical analysis results.

Specimen	Max. Test Load P_{max} (kN)	Experimental		Numerical			
		Δ(mm)	Δ(mm)	Δ (mm)	(*) (mid)	Δ (mm)	(*) (third)
RGs	40.85	16.69	14.20	16.23	0.97	13.82	0.97
G1bs(mid)	17.78	22.78	16.84	24.91	1.09	17.89	1.06
G1bs(third)	22.59	19.63	23.27	20.53	1.05	22.98	0.98
G2bs(third)	13.94	28.55	27.57	24.98	0.88	24.30	0.88
G1fs(mid)	40.37	26.80	21.38	27.11	1.01	21.92	1.02
G1fs(third)	40.46	22.40	22.46	25.10	1.12	24.60	1.09
G2fs(third)	37.00	25.75	26.07	29.63	1.15	27.83	1.07

(*) (numerical / experimental) deflection ratio.

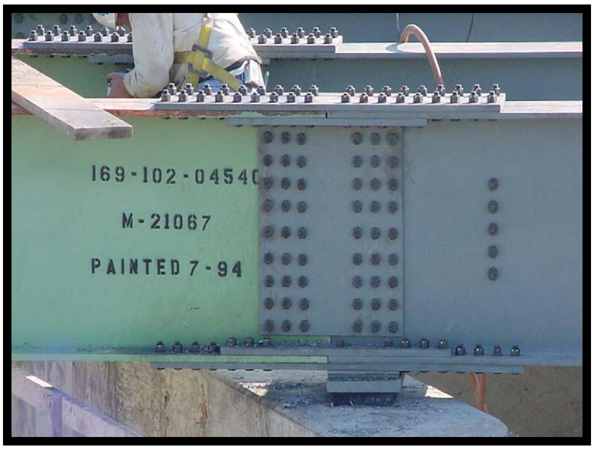

Figure 1. Typical bolted girder splice.

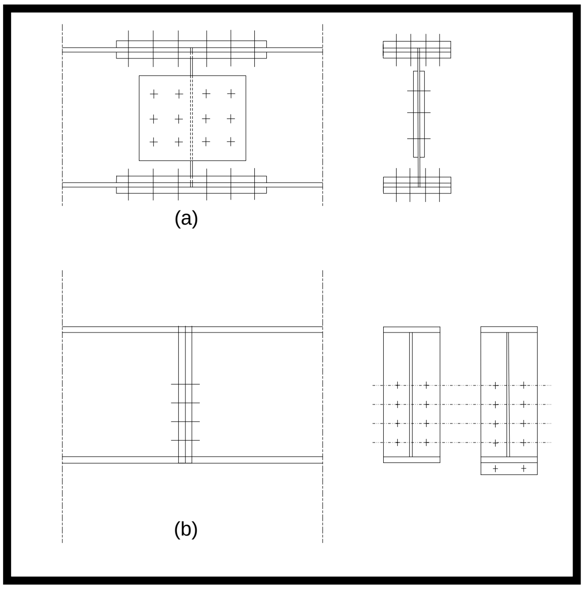

Figure 2. Girder splices
(a) web- flange splice , (b) end- plate splice .

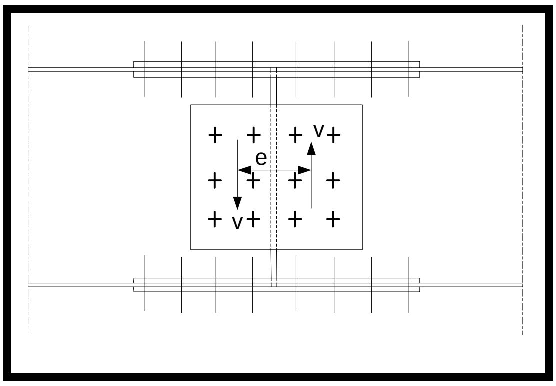

Figure 3. Design condition for bolt group in web splice[1].

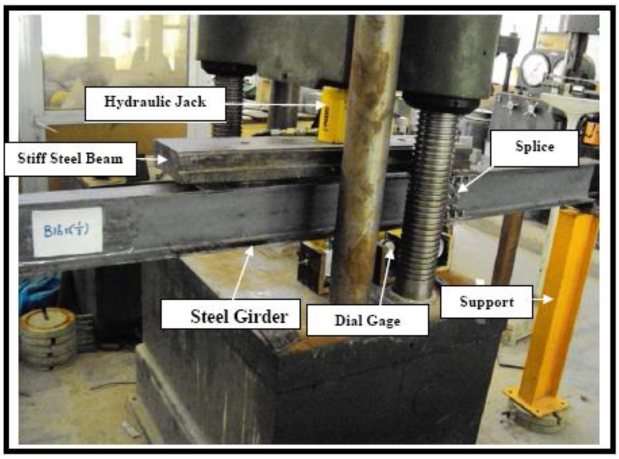

Figure 4. General view of static test setup.

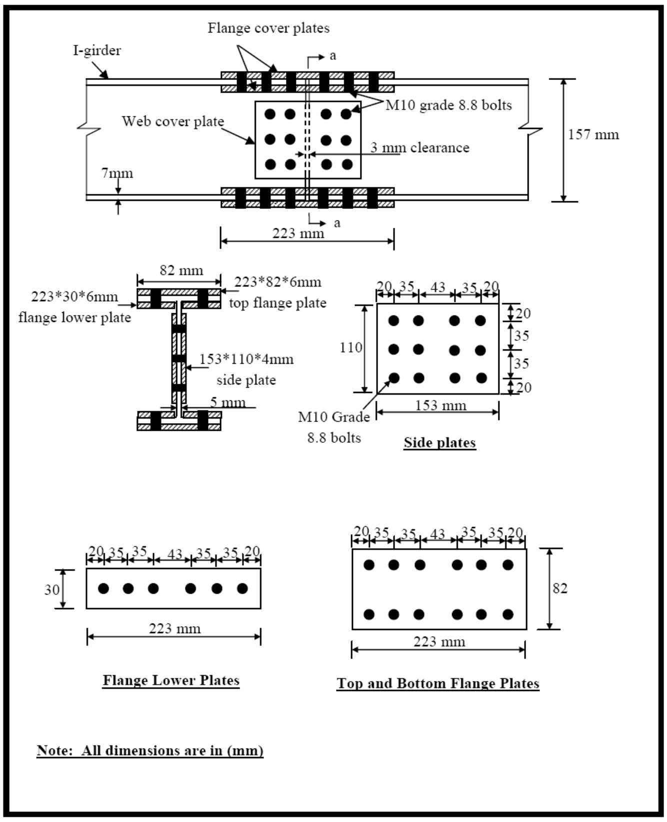

Figure 5. Details and dimensions of a bolted splice used in the experimental investigation.

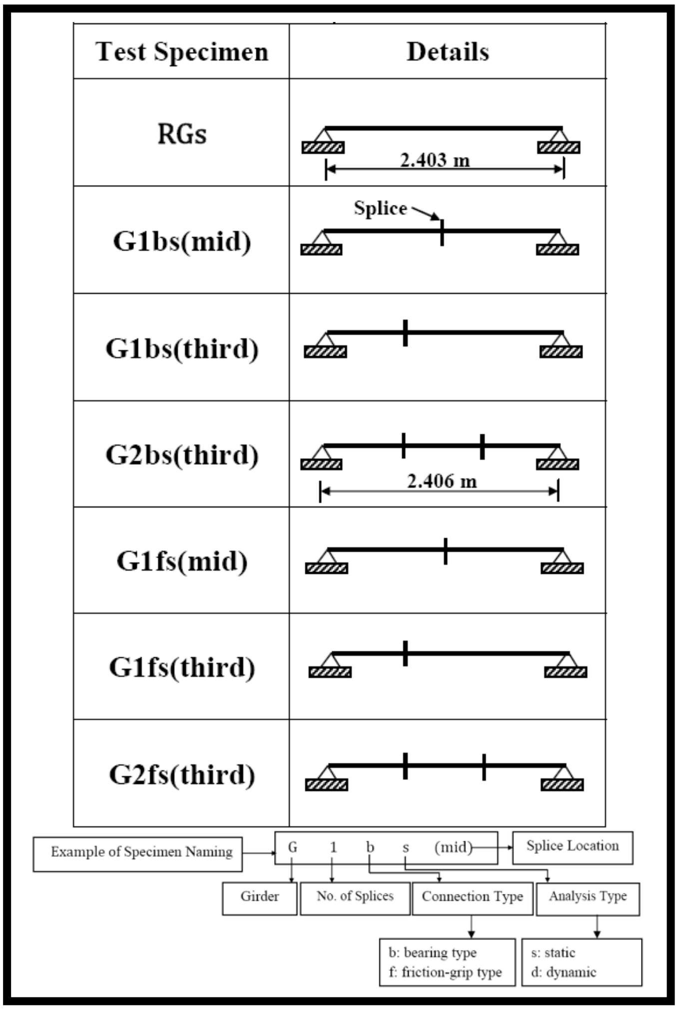

Figure 6. Details of the test specimens.

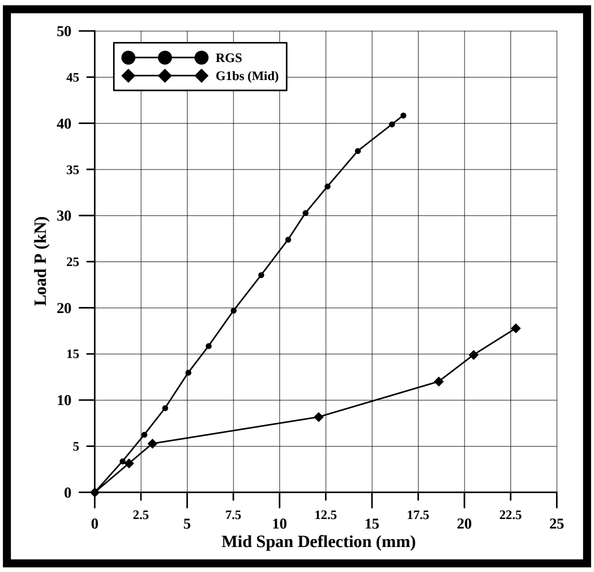

Figure 7. Load-deflection curves at midspan for RGs and G1bs(mid) **.**

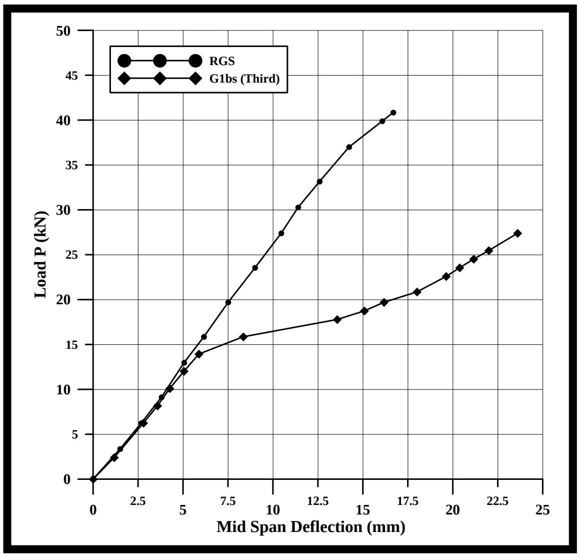

Figure 8. Load-deflection curves at midspan for RGs and G1bs(third).

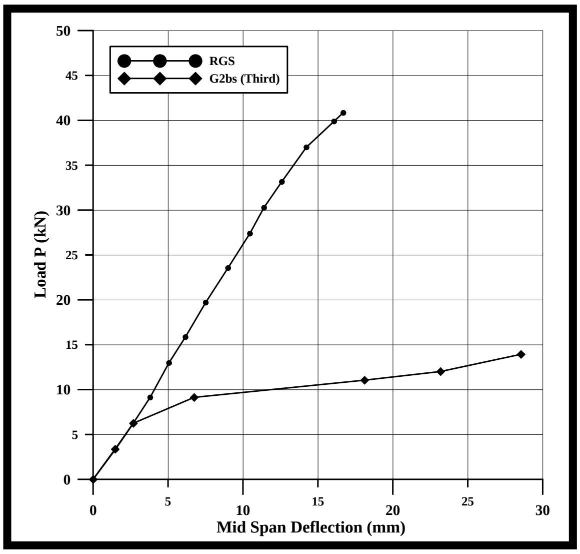

Figure 9. Load-deflection curves at midspan for RGs and G2bs(third) .

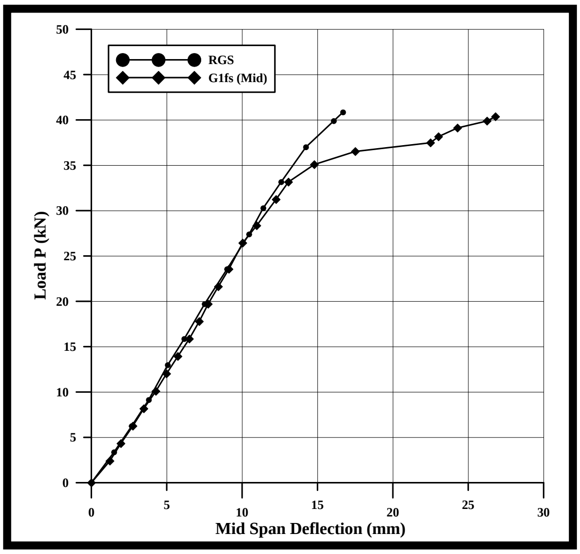

Figure 10. Load-deflection curves at midspan for RGs and G1fs(mid).

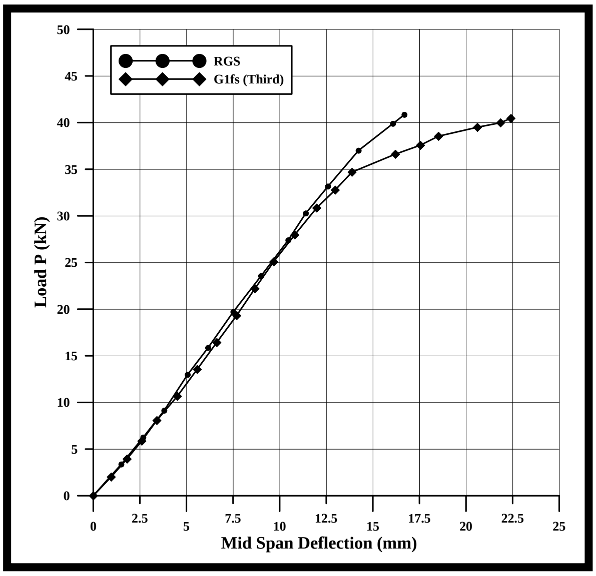

Figure 11. Load-deflection curves at midspan for RGs and G1fs(third).

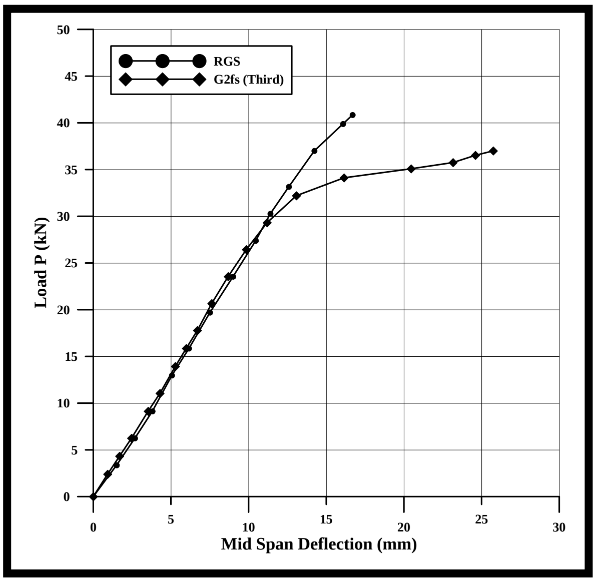

Figure 12. Load-deflection curves at midspan for RGs and G2fs(third) **.**

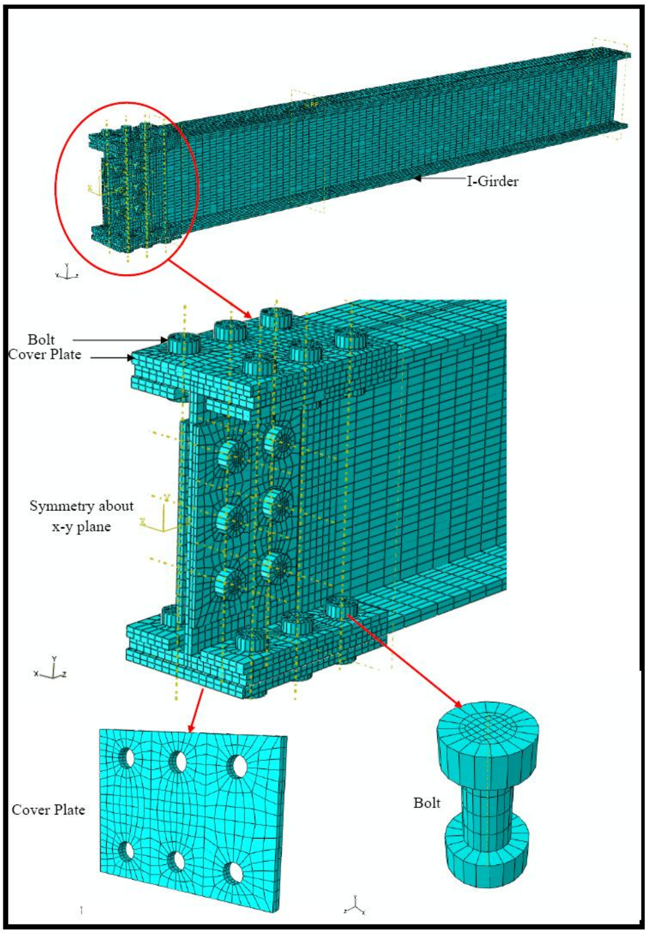

Figure 13. Finite element mesh of the model assembly for girder (G1bs(mid)).

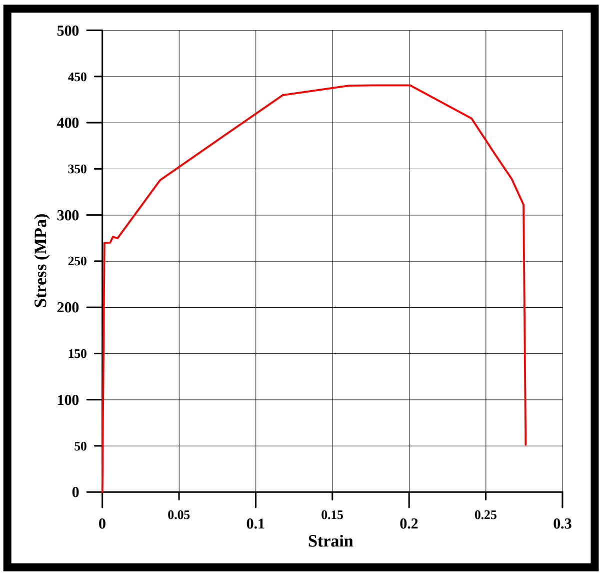

Figure 14. Stress-strain curve for I-girder.

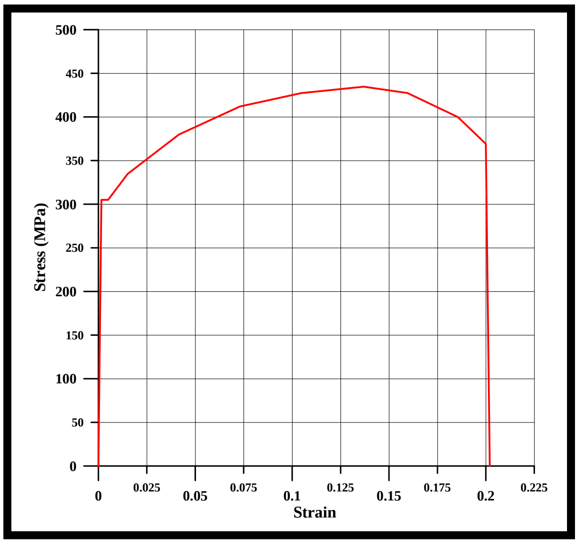

Figure 15. Stress-strain curve for cover plate(4mm).

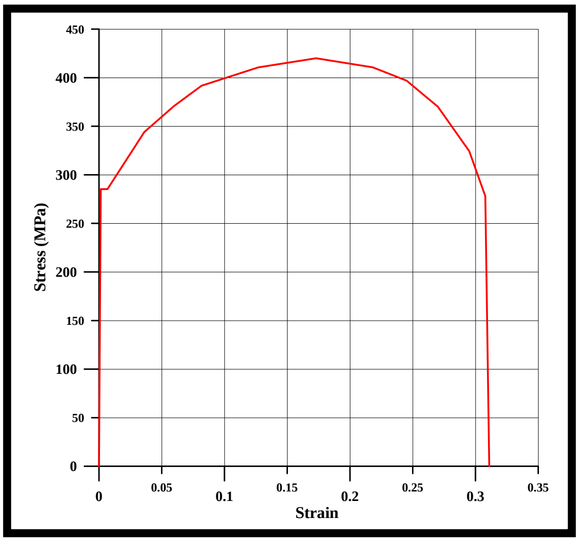

Figure 16. Stress-strain curve for cover plate(6mm).

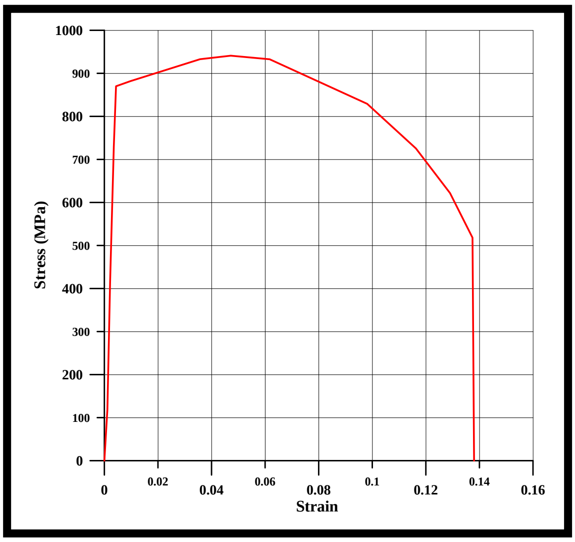

Figure 17. Stress-strain curve for bolts **.**

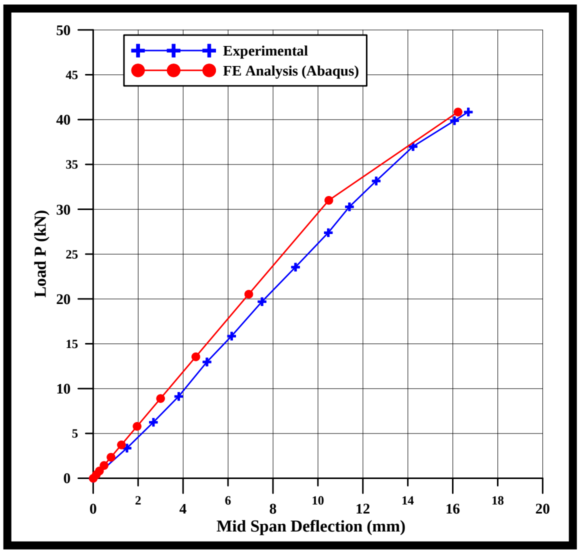

Figure 18. Load-deflection curves for reference girder RGs.

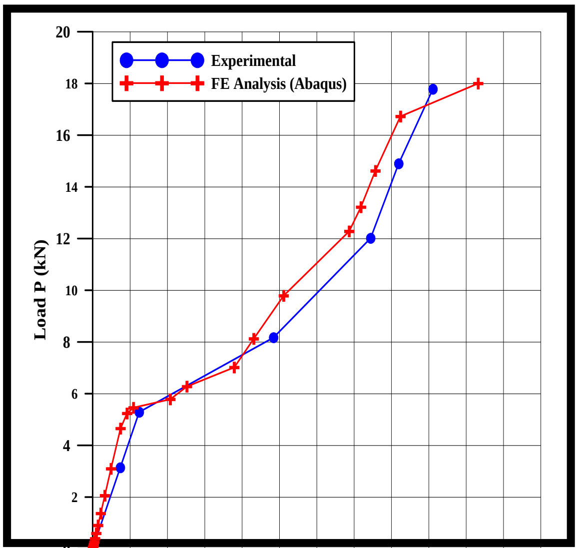

Figure 19. Load-deflection curves for girder G1bs(mid).

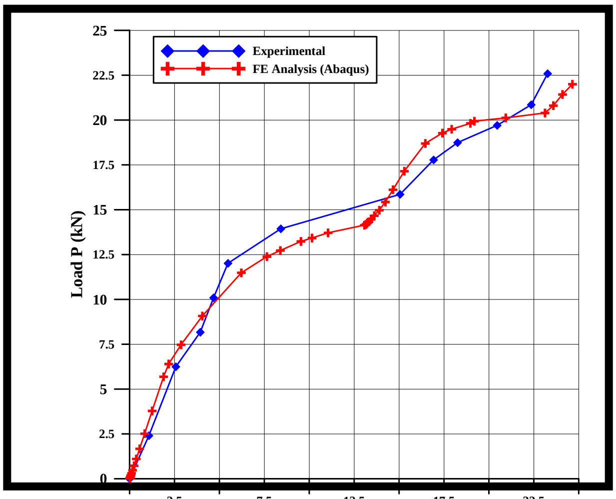

Figure 20. Load-deflection curves for girder G1bs(third).

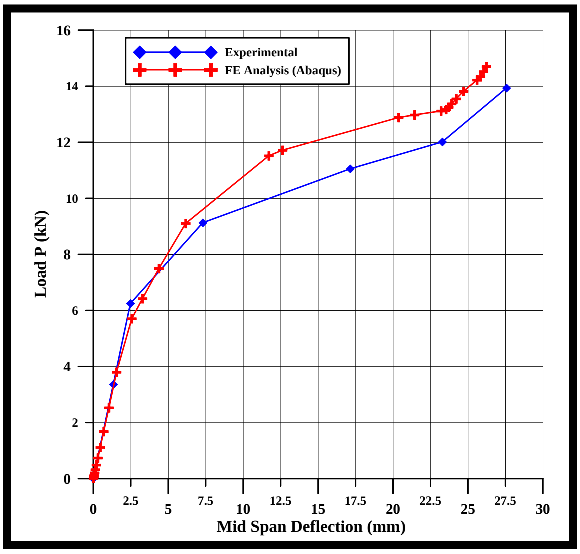

Figure 21. Load-deflection curves for girder G2bs(third).

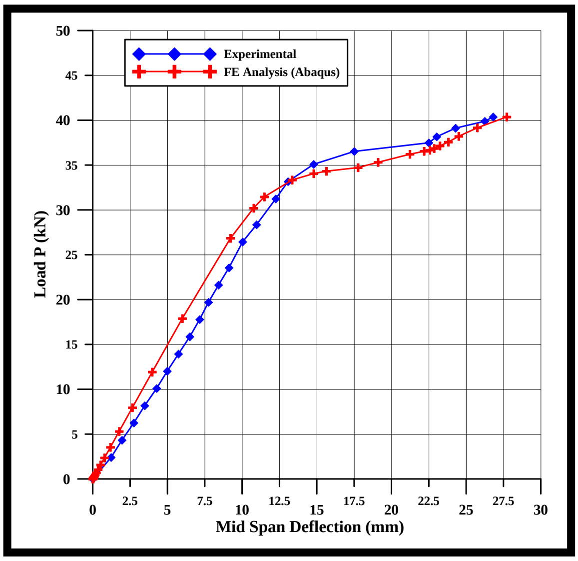

Figure 22. Load-deflection curves for girder G1fs(mid).

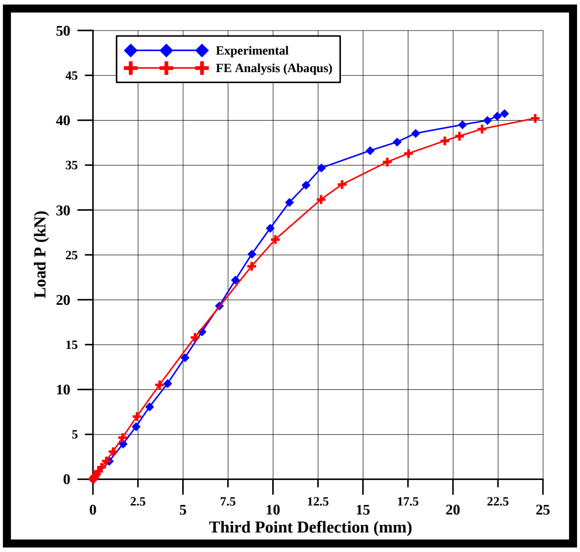

Figure 23a. Load-deflection curves for girder G1fs(third).

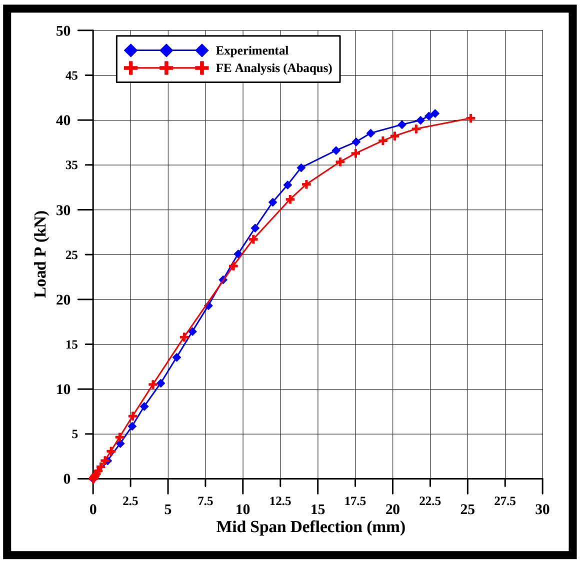

Figure 23b. Load-deflection curves for girder G1fs(third).

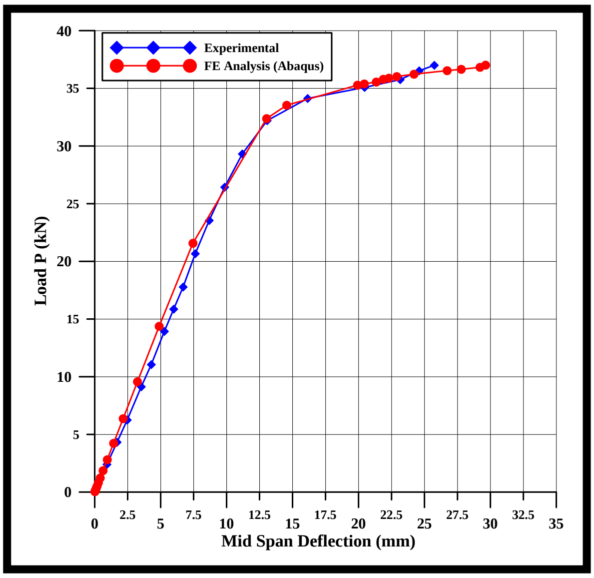

Figure 24. Load-deflection curves for girder G2fs(third).