Experimental Study on the Effect of Cross Bracing on the Behaviour of Composite Bridges

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ABSTRACT In this paper the results of an experimental program were presented to show the effect of cross bracing on the behavior of composite bridges. Two types of models were prepared in the laboratories of the American University in Cairo Egypt. These models were chosen to be one tenth scale of the model of the Federal Highway Administration (FHWA). Deflections and strains were measured for each model according to the set of bracing and comparisons were made to show the effect of bracing.

Keywords: Composite bridge, cross frame, curved bridges, experimental program.

1. INTRODUCTION

Presently, many cities face problems of space limitation for the transportation systems. One probable solution is to construct bridges with special configurations. Horizontally curved composite bridges are among the most economical options for satisfying these demands. To develop and improve a rational set of design guidelines, the Federal Highway Administration (FHWA) initiated the curved steel bridge research project in 1992, and constructed a full-scale model of curved steel girder bridge at its Turner-Fairbank Structures Laboratory. This full-scale model made it possible to conduct numerous tests and collect a significant amount of data relating to the static behavior of curved girder bridge, [1].

The most commonly used member for horizontally curved bridges is steel I-girders, which provide minimal torsional resistance and can only be considered stable if they are connected with other girders using cross-frames or diaphragms, [2].

The behavior of bridges having horizontally curved geometry complicates their design and erection. In these systems, because of the geometry of the structure, gravity loading not only causes a vertical deflection in the girder, but also twisting of the girder cross section. In this case, the cross-frames, in addition to restraining the lateral-torsional deformations, also play an important role in the distribution and transfer of load between girders and are recognized as primary members (primary members should be designed for strength and fatigue), [2], [3] and [4].

In the curved I-girder bridges the internal torsion in curved bridges exists independently of the interconnection of the girders by the cross-frames. If the curved I-girders are not connected to the overall bridge structural system by the cross-frames, they tend to exhibit large torsional deflections. The predominant resistance to the above internal torsion in horizontally-curved I-girder bridges is developed by interconnecting the girders across the entire bridge width by the cross frames [5].

Modern highway construction often requires bridges with horizontally curved alignments. According to 1991 survey [6]. Curved bridges represent 20 to 25 percent of the market for new steel bridge construction each year and this trend is likely to increase in the future. Construction of horizontally curved steel bridges is also generally more complex than construction of straight -girder bridges of similar span. Curved -girder bridges, once completed have generally performed as intended, [6].

In straight bridges, cross-frames and diaphragms are considered as secondary load carrying components, while in curved bridges, they acting as primary load carrying components, [7]. Another important structural role of cross-frames in curved bridges is the reduction of warping stress and bending stress, [8]. Furthermore, the increase on the number of cross-frames can improve the overall stiffness of the girder system. However, designers must also take into consideration the increase in its economic cost, [9].

2. DESIGN, FABRICATION, AND TESTING OF MODELS

2.1 I-girder Dimensions and Details:

The models used in this study have been scaled as one tenth of the FHWA full scale model which was used for long-term tests, Fig. 1. The composite section, then designed according to the AASHTO 2003 guide specification, [10]. The

design is based on the assumption that the neutral axis of the composite section lies in the top flange. The models are to be single simply supported span. The straight model is 2.6m length while the curved model varies from 2.87m for the outer girder to 2.33 for the inner girder. The cross frame was chosen to be X-type configurations constructed of 40*40*3 mm angle sections of steel grade 37, [11]. Steel studs were used as shear connectors with 13mm diameter of steel grade 37, Fig. 2 to Fig. 4.

The steel I-girders are chosen from IPE 160 sections, (see Table I). They are placed at 0.6m spacing. The curved girders for the curved model were curved by the roller-machine to radii R 6.36m for the outer girder, 5.673m for the middle girder and 4.56m for the inner girder. The shear connectors were welded to the top flanges of the I-girders for the two types of models.

The models were set according to the specified spacing (0.6m) and the cross frames were installed at the required positions according to predetermined spacing. A 100 mm thick concrete was casted in situ to complete the composite section. The concrete was made of strength (f_{cu}) of 38 N/mm². The concrete modulus of elasticity used in the design calculation was taken as 25 N/mm². Two layers of steel reinforcement were used from bars of 8mm and 6mm diameters, Fig. 5.

Fig. 1: FHWA curved bridge testing model

TABLE I: PROPERTIES OF STEEL I-GIRDER

Section type	IPE 160
Depth mm	160
Width mm	82
T_f	7.4
t_{web}	5
Area cm^2	20.136
Weight kg/m	15.3

Fig. 2: Steel frame plan

Fig. 3: Steel cross section

Fig. 4: Steel frame of curved model

Fig. 5: Distributions of reinforcement and form work

3. TEST SETUP AND INSTRUMENTATION

The models were tested by using a test frame and 200 Ton Static actuator with two hydraulic power systems, Fig. 8. Each model was simply supported on two braced rigid beams by a system of steel plates and rollers. The load was applied through a set of rigid beams, at six points (two on each beam). The loading system is applied so that 50 % of the total load on the middle girder and 25% on the each of the other girders, Fig. 6, and Fig. 7. In order to measure the deflection, Five linear variable differential transducer (LVDT) sensors were used, three of them to measure maximum deflection of each girder and the other two at the ends of the middle girder, Fig. 9. Also strain gauges were fixed to measure maximum strains at top and bottom flange and web of each girder.

Each model was subjected to an incremental load up to 20 Ton maximum load and resulting deflections and strains were recorded for each model and each set of cross- bracings.

Fig. 6. Plan of model load points

Fig. 7. Curved model six point for distribution

3.1 Parametric Study Testing Procedure:

To study the influence of the cross frame spacing variation, on the strain and deflection of both curved and straight models under linear static load, a parametric study was conducted.

For each model a 20-ton monotonic static load was applied in three phases;

Fig. 8. 500 Ton steel frame and two braced rigid beam

Fig. 9. Curved model instrumentations

- Firstly, for the model with only two cross frames installed at each end,
- In the second phase beside two cross frames at each end, one additional intermediate cross frame was added at the center of the model,
- And finally in the third phase beside two cross frames at each end, three additional intermediate cross frame was added at the center of the model; with spacing at 650 mm intervals across the center girder.

4. RESULTS ANALYSIS AND DISCUSSION

4.1 Deflections for Each Girder:

The load deflection curve for each girder for each model with a set of cross bracing were given in Fig. 10 to Fig. 12.

The maximum deflections measured for each girder in each model according to the set of cross bracings are given in tables (II to IV).

TABLE II: MAXIMUM DEFLECTIONS AT CENTER LINE OF INTERIOR GIRDER OF STRAIGHT AND CURVED MODELS

Cross Frames	Curved model		Straight model	
	Maximum Deflection (mm)	Percentage difference	Maximum Deflection (mm)	Percentage difference
Two	2.066		2.066	
Three	2.89	28.5%	2.066	0%
Five	3.29	22.62%	1.65	20.13.4%

Fig. 10. Deflection at the center line of interior girder of straight and curved models

Fig. 11. Deflections at middle girder of straight and curved models

TABLE III: MAXIMUM DEFLECTION AT MIDDLE GIRDER OF STRAIGHT AND CURVED MODELS

Cross Frames	Curved model		Straight model	
	Maximum Deflection (mm)	Percentage difference	Maximum Deflection (mm)	Percentage difference
Two	3.60		2.13	
Three	3.39	5.83%	1.84	13.62%
Five	3.2	5.6%	1.84	0%

Fig. 12. Deflection at exterior girder of straight and curved models

TABLE IV: MAXIMUM DEFLECTION AT EXTERIOR GIRDER OF CURVED AND STRAIGHT MODELS

Cross Frames	Curved model		Straight model	
	Maximum Deflection (mm)	Percentage difference	Maximum Deflection (mm)	Percentage difference
Two	4.34		2.66	
Three	4.03	7.14%	2.66	0 %
Five	3.72	7.7%	1.65	38%

4.2 Strains for Each girder:

The load strain curves measured for each girder for each model with a set of cross bracings were shown in Fig. 13 to Fig. 17.

The maximum strains were also given in table (V to VIII).

Fig. 13. Strain at the center line of bottom flange of interior girder for straight and curved models

TABLE V: MAXIMUM STRAIN AT BOTTOM FLANGE OF INTERIOR GIRDER (G1) FOR STRAIGHT AND CURVED MODELS

Cross frame	Maximum strain µm/m	Maximum strain µm/m	Maximum strain µm/m
	Two cross frames	Three cross frames	Five cross frames
Curved model	212.9	116.7	68.8
Straight model	222	204.7	202.8
Percentage difference	4.9%	43%	68.57%

4.3 DISCUSSIONS OF RESULTS

Tables (II to IV) show the behavior of curved and straight models towards cross frame spacing. In the curved model the maximum deflection occurred in exterior girder (4.34 mm). The deflection value of the curved model was higher

than that of the straight model by 42.5 %, because the configuration of the curved model induces lateral flange moment and torsion moments and the span is longer than others.

Fig. 14. Strain at bottom flange at the center line of middle girder for straight and curved models.

Fig. 15. Strain at bottom flange at the center line of exterior girder for straight and curved models

TABLE VII: MAXIMUM STRAIN AT BOTTOM FLANGE OF EXTERIOR GIRDER FOR STRAIGHT AND CURVED

	Maximum strain	Maximum strain	Maximum strain
Cross frame	μm/m	μm/m	μm/m
	Two cross frames	Three cross frames	Five cross frames
Curved model	288.9	296.6	327.2
Straight model	172.2	174.1	170.3
Percentage difference	40.4%	41.3%	48%

The spacing between cross frame affects the total deformation of the curved model clearly, where the deflection decrease with increasing of numbers of cross frame. As shown in tables (I TO IV) for the middle and exterior girders, the increase in the number of cross frame from two to three resulted in decrease the maximum deflection (5.83% and 7.14% respectively), but slight decrease was noticed in the deformation

when additional two cross frames were installed.

Fig. 16. Strain at tension zone of web of interior girder for straight and curved models with three cases of cross frame

Fig. 17. Strain at web tension zone of exterior girder for straight and curved models with three cases of cross frames

TABLE VIII: MAXIMUM STRAIN AT TENSION ZONE OF WEB OF EXTERIOR GIRDER FOR STRAIGHT AND CURVED MODELS

	Maximum strain	Maximum strain	Maximum strain
Cross frame	μm/m	μm/m	μm/m
	Two cross frames	Three cross frames	Five cross frames
Curved model	568.39	396.1	415.29
Straight model	103.34	88.03	84.207
Percentage difference	81.81%	77.77%	79.72%

The interior girder behaves differently, the deflection was increased with increasing the numbers of cross frames, this may be due to the transmission and redistribution of the applied load caused by the cross frames towards the shorter span girder.

In the straight composite model the effect of a number of cross frame more than three is negligible. This confirms the assumption that cross frame is as secondary member.

Tables (V to VIII) illustrate the effects of spacing between cross frames on the strain values for both

curved and straight models. For both curved and straight models, the strain values behave normally (increasing with the load increasing). But the strain values of the curved model were higher when they compared with the straight model values. (The difference reaches 80% in the web and 48% in the bottom flange for exterior girder). Torsion moment in the curved model increases the stresses in the whole structure that may be due to the influence of curvature.

5. CONCLUSIONS AND RECOMMENDATIONS

- The straight model shows stiffer behavior than the curved model. Because it shows less deflection.
- The effect of Cross frame in straight model negligible for more than three cross frames.
- In the curved model, the use of the cross frame is essential.
- As the recommendation, for future experimental work the cross-section of the I-girders should be chosen to cater for the load distribution.
- An optimum spacing of the cross frame in real structure should be obtained from experimental of prototype of full scale of composite bridge.

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