Behavior of Concrete-Filled Steel Grid Decks

HOTA V. S. GANGARAO, PENMATSA R. RAJU, AND
NARSIMHA R. KOPPULA

The experimental findings of the current research on concrete-filled steel grid decks are presented. These findings are based on testing seven specimens (one open and six concrete-filled decks). Experimental tests have been conducted in elastic as well as post-yielding ranges, and consequent deflection and strain data are critically reviewed and reported. External composite action of concrete-filled steel grid decks with wide-flange steel stringers is studied and discussed. Similarly, strain incompatibility of internal composite action between steel grid deck members and concrete fill (referred to as incomplete internal composite action) is established with the aid of strain gauge readings, and the data are synthesized and presented. Analytical results, based on the orthotropic plate theory, are developed and their correlations with experimental strains and deflections are presented. Excellent correlation of theoretical results with the experimental results is noted in the elastic range.

Bridge deck maintenance and rehabilitation are major problems currently faced by the transportation industry in the United States. The aging bridge infrastructure needs billions of dollars for rehabilitation of bridge decks to bring them up to acceptable standards (*1*). The life-cycle cost of conventional reinforced concrete slab is becoming a heavy financial burden because of either frequent maintenance and repair or rehabilitation and replacement. Concrete-filled steel grid decks, on the other hand, have been used to rehabilitate many bridge decks to reduce the dead load, widen existing decks, increase the load-carrying capacity of supporting stringers, and economically rehabilitate aging bridge decks. These decks are ideal as bridge decking material in movable and long-span bridges because of their low self weight of about 40 to 60 lb/ft^2 when compared with concrete decks that weigh about 110 lb/ft^2. About 25 million ft^2 of steel grid decks is in use in the United States (*2*) (unpublished data, Bridge Grid Flooring Manufacturers Association). Concrete-filled grid decks share about 75 to 80 percent of total bridge grid deck area now in use. Concrete-filled steel grid decks have been used in many major bridges, such as the Walt Whitman Bridge (1956), Mackinac Straits Bridge (1957), Verrazano Narrows Bridge (1964), and others. Some of them have been in use for more than 60 years and have exhibited excellent performance characteristics.

Manufacturing and installation costs of concrete-filled grid decks vary from about \$20 to \$25/ft^2, depending on the type of steel grid deck, concrete filler, and other construction constraints. Open steel grid decks are either rectangular or four-way types. Steel grid decks are factory assembled and consist of main and secondary (cross) bars positioned perpendicular to each other. The bars are mechanically interlocked and welded or riveted at their intersections. Tertiary bars may be added to run in the middle of main bars. Concrete may be placed to the full depth, half depth of the grid deck with or without overlay, or just over the grid deck (exodermic). The fully filled grid deck is shown in Figure 1.

In spite of their long usage, longitudinal growth of filled grids, cupping and cracking of concrete overlay, and weld failures between stringers and filled decks have been reported as maintenance problems (*1,2*). In addition, there are no satisfactory analytical methods available to predict the elastic and ultimate strength behavior of concrete-filled decks under applied static loads. No satisfactory design criteria have been established to check the strength and stiffness of concrete-filled steel grid decks.

The major objective of this study is to understand the pre- and postcracking strength and stiffness behavior of fully filled concrete grid decks under out-of-plane static loads, with emphasis on internal composite action between grid bars and concrete, external composite action between filled grid and wide-flange stiffening beams, elastic and ultimate moments, and simple theoretical correlations with the experimental data. Many other important issues, including fatigue behavior, deck growth phenomenon, and improvements in stiffness, are being researched and will be published as a sequel to this work.

All new specimens (Specimens 1 through 4 and 7) are 12 ft long and 6 ft wide. The old specimens (Specimens 5 and 6) are 14 ft long and 6 and 5.5 ft wide, respectively. For all specimens, main bars run in the long direction except for Specimen 3, where main bars run in the short direction. All steel grid decks are 4.25 in. deep, but the total depth of Specimens 4 through 6 varies with overlay. Cross bars are spaced at 4 in. in all specimens, whereas main bars are spaced

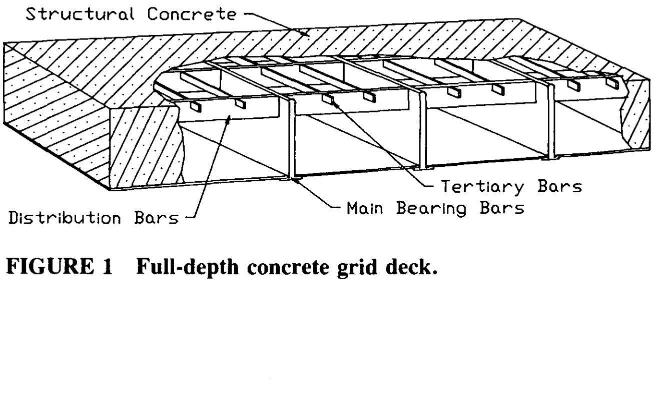

FIGURE 1 Full-depth concrete grid deck.

H. V. S. GangaRao and P. R. Raju, College of Engineering, West Virginia University, Morgantown, W. Va. 26506-6101. N. R. Koppula, Bechtel Power Corporation, Gaithersburg, Md. 20877.

TABLE 1 Description of Specimens Used for Testing

SPECIMEN NUMBER	TYPE OF GRID DECK	STATUS**	SPECIMEN SIZE	MAIN BAR DIR.	MAIN BAR SPACING	TOTAL DEPTH OF SPECIMEN	CONCRETE STRENGTH (PSI)
1	OPEN	NEW	6' X 12'	LONG	8"	4.25"	-
2	FULLY FILLED	NEW	6' X 12'	LONG	8"	4.25"	4600
3	FULLY FILLED	NEW	12' X 6'	SHORT	8"	4.25"	7300
4	FULLY FILLED WITH 2 1/8" OVERLAY	NEW	6' X 12'	LONG	8"	6.375"	4500
5	FULLY FILLED WITH 0.375" OVERLAY	OLD*	6' X 14'	LONG	6"	4.625"	4000 (ASSUMED)
6	FULLY FILLED WITH 0.19" OVERLAY	OLD*	5.5' X 14'	LONG	6"	4.44"	4000 (ASSUMED)
7	FULLY FILLED	NEW	6' X 12'	LONG	8"	4.25"	4000

*TERTIARY BARS ARE SPACED AT 6" BETWEEN THE MAIN BARS

**EXODERMIC DECK TEST RESULTS WILL BE PRESENTED AS A SEQUEL TO THIS PAPER

- CONCRETE IS NOT PRESENT

at 8 in. and 6 in. for new and old decks, respectively. Old specimens have tertiary bars at 6-in. spacing and are in the direction of main bars. No tertiary bars are present in new specimens. Concrete strength used in new specimens is indicated in Table 1. Concrete strengths of old decks are not known, because no data are available. However, for analysis purposes, concrete having 4,000 lb/in.^{2} strength is assumed. The two old specimens were removed from the Hall Station Bridge over Union Railroad at Monraville and brought to the Major Units Laboratory, West Virginia University (WVU), to find strength and stiffness of old decks. One end of each old deck was severely damaged during its removal. The severely damaged end was avoided, and testing was carried out on a 10-ft span.

About 100 tests on seven specimens have been conducted to study the elastic and ultimate behavior of concrete-filled steel grid decks. The influence of internal and external composite action on the stiffness of concrete-filled decks was studied. Experiments on flexural behavior, including transverse load distribution, load sharing, and deformations, were also carried out on open decks for comparison with concrete-filled grid decks. Experimental data were collected using four to six strain gauges and four dial gauges. Detailed information on testing can be obtained elsewhere (*3*).

OPEN VERSUS CONCRETE-FILLED DECKS

Static tests were conducted to measure the flexural stiffness of open and concrete-filled grid decks. The study reveals a substantial increase in strength and stiffness of open decks when filled with concrete (Table 2). The two-beam and three-beam experimental test set-ups were used to carry out the load tests. The two-beam set-up was the same as the three-beam set-up except for removing the central beam and retaining the end beams. In the two-beam set-up, the maximum test span of 11.5 ft for new open concrete-filled decks and 10 ft for old filled decks are used in the experiments. A 10- by 20-in. loading pad was placed at the geometric center of a deck to simulate dual truck tires and oriented so that traffic flow was parallel to the main bars. Load versus deflection curves for an open grid deck (Specimen 1), and new concrete-filled steel grid decks (Specimens 2 through 4 and 7) are presented in Figure 2 because they have similar geometric properties.

For comparison of new filled decks with old filled decks, bending stiffness of all the decks tested in the elastic range is shown in Table 2. Fully filled decks (Specimens 2 and 7) without overlays are about 2.5 times stiffer in the main bar direction than an identical open steel deck without concrete, and they are about 4 times stiffer in the main-bar direction than in the cross-bar direction because of main- and cross-

TABLE 2 Flexural Stiffness of Various Decks

Specimen number	Spanning bar & spacing	Span Ft.	Type of deck	Stiffness of the specimen (kips/in)
1	Main bar @8"	11.5	Open	9.92
2	Main bar @ 8"	11.5	Filled	22.61
3	Cross bar @ 4"	11.5	Filled	6.62
4	Main bar @ 8"	11.5	Overlaid	68.5
5	Main bar @ 6"	10	Filled	60.6
6	Main bar @ 6"	10	Filled	50.0
7	Main bar @ 8"	11.5	Filled	26.88

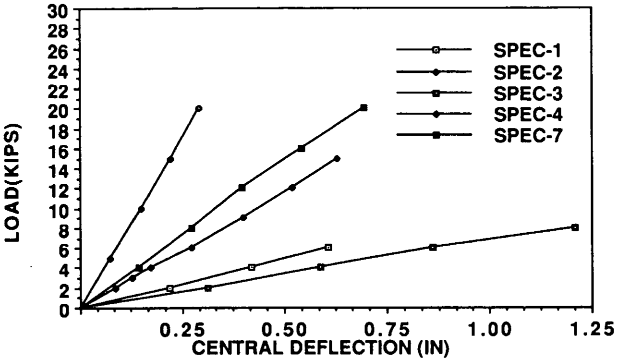

FIGURE 2 Load deflection of open and concrete-filled decks for span of 11.5 ft.

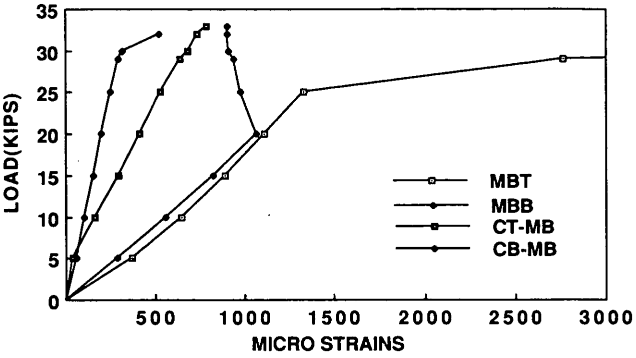

FIGURE 3 Load strains of Specimen 7 at ultimate load.

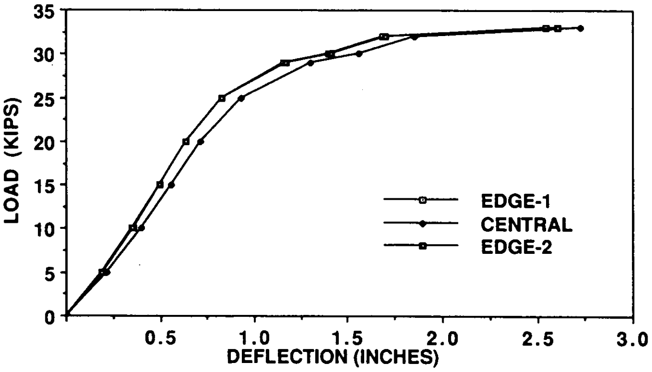

FIGURE 4 Load deflection of Specimen 7 at ultimate load. Deflections at Edges 1 and 2 are coinciding.

bar stiffness variations (i.e., the orthotropic nature of the deck system). Low stiffness is noted in Specimen 3 as it spanned in the cross-bar direction, whereas others are spanned in the main-bar direction. The flexural rigidities of the fully filled deck in main- and cross-bar directions are 26.62×10^3 and 7.65×10^3 ksi/in., respectively. The ratio of flexural rigidities in main and cross-bar directions is about 3.5, which results in greater stiffness in main-bar direction over cross-bar direction. The deck with overlay of 2⅛ in. (Specimen 4) is around 2.75 times stiffer than fully filled decks (Specimens 2 and 7). In fully filled decks, Specimen 7 showed about 18 percent higher stiffness than Specimen 2, which is attributed to the type of concrete (4,600 lb/in.^{2} versus 4,000 lb/in.^{2}) and the curing method (wrapped in plastic versus daily watering). Old concrete-filled decks are stiffer than new filled decks because of the differences in span length, main bar spacing, and tertiary bars in new and old decks.

INTERNAL COMPOSITE ACTION

Internal composite action is related to the degree of strain compatibility between the steel grid and the concrete that fills the open cells of a steel grid. The degree of strain compatibility between steel and concrete is investigated by measuring strains on both steel and concrete at the top and bottom of the deck. Typical load-versus-strain and load-versus-deflection plots for Specimen 7 are presented in Figures 3 and 4, respectively. In the precrack state, low tensile strains in concrete and high tensile strains in steel indicate poor adhesive bond between the steel grid deck and the concrete in the tension zone at the bottom of the deck. Therefore, tensile force in steel is fully accounted for, whereas tensile force in concrete is neglected.

Hairline shrinkage cracks were observed along the main bars in concrete-filled grid decks (Specimens 2, 3, and 7). The main-bar strains at the top of a deck (MBT) are about two to four times higher than the concrete strains (CT-MB) (Figure 3). Thus, strain incompatibility between steel and concrete is observed and is attributed to the lack of full adhesive bond between the steel main bars and concrete. The lack of adhesive bond is confirmed by the presence of the hairline cracks observed along the main bars in all specimens of fully filled decks except overlaid deck (Specimen 4). The cracks are believed to be caused by shrinkage of concrete between two contiguous main bars. The old decks showed better strain compatibility between steel and concrete than did new decks (Figures 3 and 5). Bulking of individual steel grid I-bars caused by rusting had filled the cracks between the steel main bar and the concrete (*2*) and thus improved adhesive bond. This phenomenon was observed in old decks. Other reasons for better compatibility in old decks are (a) main bar spacing (6 in. compared with 8 in. of new decks); (b) use of tertiary bars between main bars; (c) concrete overlay of 0.2 to 0.4 in. over the main bars, resulting in minimal shrinkage cracks; (d) type of concrete; (e) age of concrete; (f) effect of environmental loads; and (g) chloride concentration leading to corrosion. A summary of strains and neutral axes of various specimens is given in Table 3.

Strain incompatibility, as measured by the ratio of steel to concrete strain at the same location, decreased with the increase in applied load. This phenomenon is attributed to closure of cracks caused by compression on the top surface of the deck. However, the strain incompatibility (inability of steel bars and concrete to act together) in filled decks increased with repeated static tests, thus confirming poor adhesive bond between the steel grid deck and the concrete. For example, strain incompatibility in the compression zone of Specimen 7 (strains on top of steel main bar and concrete are 952×10^{-6} and 497×10^{-6}, respectively) increased from about 2 to about 3 (strains on top of steel main bar and concrete are $1,107 \times 10^{-6}$ and 414×10^{-6}, respectively) as

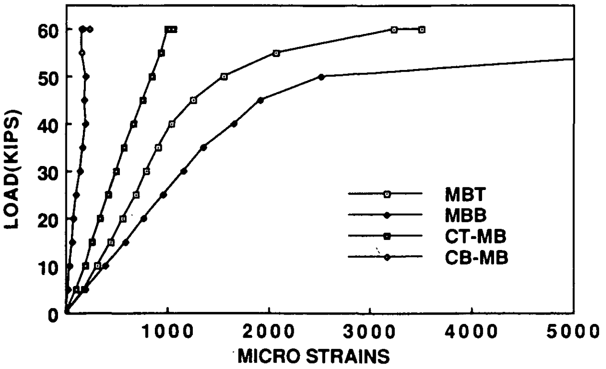

FIGURE 5 Load strains of Specimen 5 at ultimate load.

testing progressed. A similar trend was observed for all new specimens.

Concrete-filled decks were tested to study the flexural behavior in tension. It was observed from neutral axis location and strain readings that the adhesive bond effects between steel and concrete are negligible (see Table 4). Internal force equilibrium is evaluated by accounting for the degree of strain compatibility in the deck. The internal resisting (experimental) moment is arrived at from internal forces that are computed from strain gauge readings and is verified with the theoretical moment computed from the orthotropic plate theory. The experimental and theoretical moments of concrete-filled decks compared well (Table 4). Similarly, the measured deflections compared well with the theoretical deflections derived from the orthotropic plate theory. The details of ortho-

TABLE 3 Summary of Strains for Various Specimens for 10 Concentrated Loads at Mid-Span

SPECIMEN DESCRIPTION	MAIN BAR SPAN	MICRO STRAINS						TOTAL DEPTH OF DECK (IN)	N. AXIS IN MAIN BAR FROM TOP OF DECK (IN)	N. AXIS DEPTH RATIO
		COMPR.ZONE		RATIO	TENSION ZONE		RATIO			
		STEEL	CONC		STEEL	CONC				
SP-2 (M.BAR-12')	11.5"	605	228	2.65	765	56	13.7	4.25	2.07	0.487
SP-3 (M.BAR-6')	6'	267	79	3.38	315	44	7.16	4.25	2.12	0.498
SP-4 (M.BAR-12') (21/8"OVERLAY)	11.5'	386*	220	1.75	446	4	112	6.375	3.09	0.485
SP-5 (OLD DECK-1) (.38"OVERLAY)	10'	194*	248	0.78	378	44	8.59	4.44	1.725	0.373
SP-6 (OLD DECK-2) (.19"OVERLAY)	10'	232*	253	0.916	312	26	12	4.625	2.275	0.517
SP-7 (M.BAR-12')	11.5'	517	258	2	537	97	5.54	4.25	2.215	0.52

*M.BAR TOP STRAINS EXTRAPOLATED TO TOP OF CONCRETE WEARING SURFACE

TABLE 4 Comparison of Theoretical and Experimental Results for 10-kip Point Load at Center of Span (test set-up 5)

SPECIMEN NUMBER	SPAN (FT)	DEFLECTION (IN)				L.L.D MOMENT (KIP-IN) PER FOOT OF DECK	
		THEORETICAL		EXPERIMENTAL			
		CENTRAL	EDGE	CENTRAL	EDGE	THEORETICAL	EXPERIMENTAL
2	11.5	0.333	0.315	0.410	0.368	55.20	71.86
4	11.5	0.140	0.134	0.124	0.132*	55.80	70.63
5	10	0.156	0.138	0.164	0.157	47.48	54.00
6	10	0.179	0.162	0.203	0.143	50.57	51.42
7	11.5	0.335	0.315	0.344	0.305	55.20	59.66

*EDGE DEFLECTIONS ARE HIGHER BECAUSE OF SUPPORT SETTLEMENTS tropic plate theory and the methodology to arrive at the theoretical moments and deflections are given elsewhere (*3*).

EXTERNAL COMPOSITE ACTION

The degree of external composite action of concrete-filled decks with their supporting system is measured. To evaluate this composite action, the analysis considered force equilibrium, strain compatibility, shift in neutral axis of stringer, reduction in stringer deflections, and shear lag along the deck width. Concrete-filled decks are stiffened by three wide-flange steel beams spaced at 6 ft in the short direction of the decks. Composite action was achieved between the stringers and the deck by high-strength friction grip bolts. Load-strain and load-deflection plots for composite and noncomposite behavior of the central stringer with Specimens 2 through 4 and 7 are given in another report (*3*). However, only the composite behavior of the central stringer with Specimen 7 is shown in Figures 6 and 7. Strain gauges were placed across the span direction of filled decks to measure strain variations caused by shear lag along the width of the deck. The strain variations corresponding to the distance from the central stringer are plotted for Specimens 2 and 3 in Figures 8 and 9. These plots clearly demonstrate the shear lag along the width of the deck. From strain diagrams on Specimen 7, shown in Figure 10, it is concluded that only partial composite action is achieved between flange stringers and the deck. As an example, the filled grids subjected to a concentrated load on the middle stringer are considered for the evaluation of composite action. The applied concentrated load is transversely distributed among the three stringers in proportion to the measured deflections of the stringers. The load distribution is verified from the WVU method developed from orthotropic plate theory (*4*). The experimental and theoretical transverse load distributions among the stringers correlated well with the experimental data (Table 5).

The external moment, bending, and shear deflections of the middle stringer are computed from this distributed load. Total theoretical deflection of the middle stringer is the sum of bending and shear deflections. Comparison of total theoretical deflections with measured deflections is found to be good; a maximum variation of 17 percent is noted in Table 5. The old concrete-filled grid decks (Specimens 5 and 6) were not tested for composite action with stiffening beams.

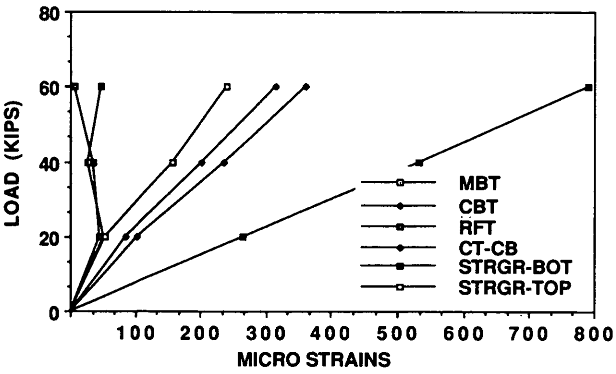

FIGURE 6 Load strains of composite stringer of Specimen 7.

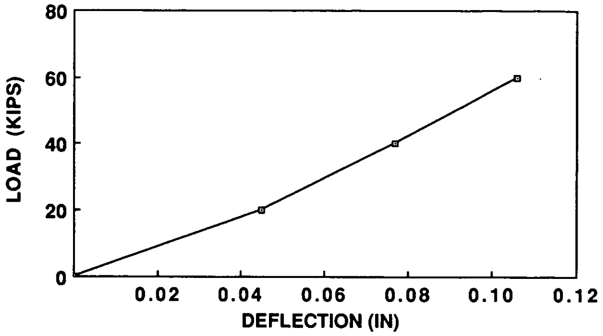

FIGURE 7 Load deflection of central stringer in Specimen 7 for composite action.

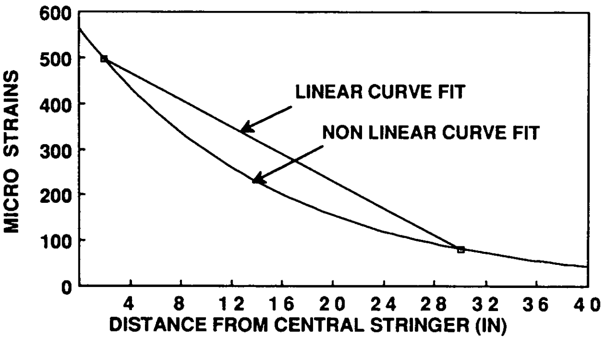

FIGURE 8 Distance strains in cross bars along the flange (filled deck) of composite stringer of Specimen 2 for a load of 40 kips on central stringer.

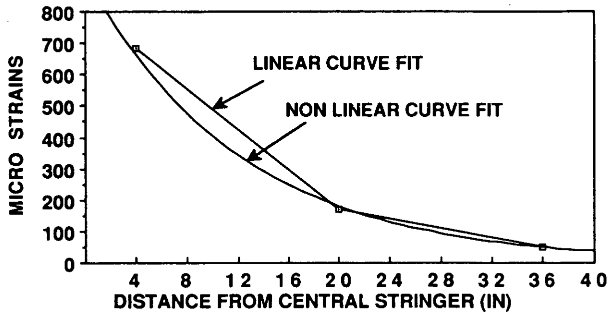

FIGURE 9 Distance strains (shear lag) in main bars along the flange (filled deck) of composite stringer in Specimen 3 for a load of 40 kips on central stringer.

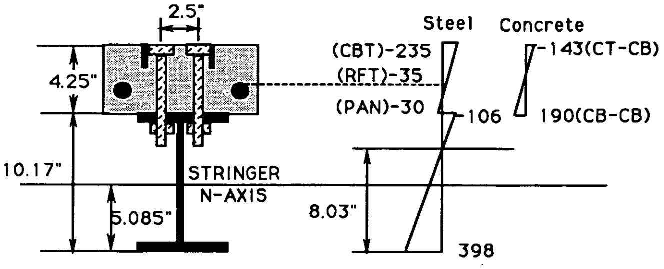

FIGURE 10 Strain diagrams for composite stringer with Specimen 7 for 30-kip load.

TABLE 5 Theoretical and Experimental Deflections of Concrete-Filled Grid Deck Composite with Wide-Flange Beams

Specimen number	Deflections (in)			
	Theory			Measured
	Bending	Shear	Total	
2	0.031	0.010	0.041	0.034
3	0.034	0.009	0.043	0.039
4	0.019	0.006	0.025	0.023
7	0.026	0.008	0.034	0.031

TABLE 6 Effective Flange Widths of Composite Stringer with Shift in Neutral Axis

Spec. No.	Shift in N.axis (in)	Effective flange width required for shift (in)	Deflections(in)			
			Theory			Experimental
			Bending	Shear	Total	
4	4.805	11.4	0.011	0.006	0.017	0.023
7	3.069	9.15	0.017	0.008	0.025	0.031

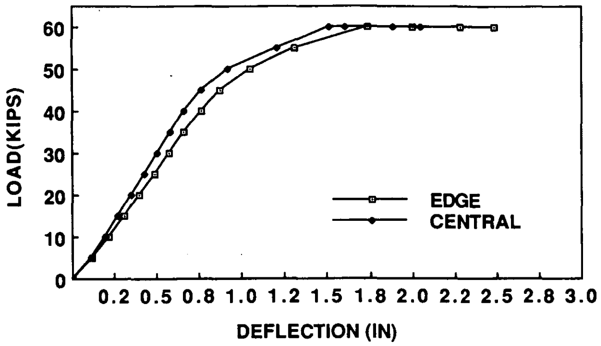

FIGURE 11 Load deflection of Specimen 5 at ultimate load.

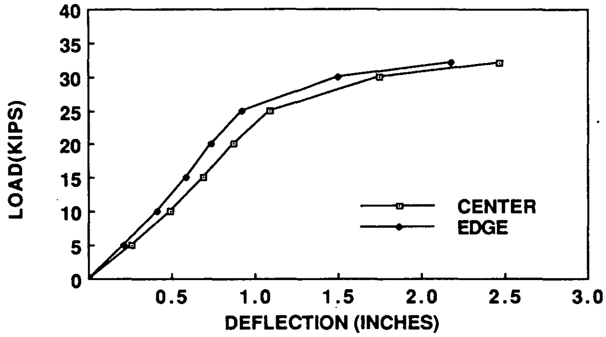

FIGURE 12 Load deflection of Specimen 2 at ultimate load.

THEORETICAL EVALUATION

A simple approach was adopted to calculate the effective width of the deck for external composite action based on the shift in the neutral axis of the stringer from its centroid. The shift in the neutral axis is measured from the strain readings in the stringer for the composite case. An equivalent deck area is derived to compute the shift in the neutral axis. A composite stringer moment of inertia is computed using the equivalent area. The bending and shear deflections are computed using the composite moment of inertia. The shifts in the computed and measured deflections of the neutral axes' depths and effective flange widths are given in Table 6. The theoretical procedure is presented in another study (*3*).

ULTIMATE MOMENT

All the concrete-filled decks (Specimens 2 through 7) were tested to their ultimate load-carrying capacity. The two-beam experimental set-up was used for the ultimate loading test. The dial gauge locations were at the center, the edge of the deck, and also at the center of the edge beam. Load-versus-strain and load-versus-deflection data for all specimens were measured (*3*). Load-versus-strain gauge readings for a new filled deck (Specimen 7) and an old filled deck (Specimen 5) are shown in Figures 3 and 5. Similarly, load-versus-deflection data for these specimens are shown in Figures 4 and 11.

Open (Specimen 1), concrete flush-filled (Specimens 2 and 7) and 2⅛-in. overlaid (Specimen 4) decks have 11.5-ft spans. For these specimens, yielding of steel bars was observed at about 7, 16, 22, and 28 kips, respectively. The open deck (Specimen 1) was not tested beyond the elastic range. Therefore, load was obtained by linear extrapolation of strains.

Ultimate load tests for these specimens showed that bottom steel yielded first in all the specimens except Specimen 7. Concrete reached its crushing value (strain of 0.003) only in Specimen 4, which has a 2⅛-in. overlay. Other fully filled concrete specimens did not reach the concrete crushing value because of strain incompatibility between steel and concrete in the compression zone.

In fully filled decks, the global deck deflections showed linearity beyond local yielding of main bars. This shows that there is a considerable degree of indeterminacy in the concrete-filled decks that leads to redistribution of loads. Post-yielding linearity is observed in up to about 50 percent and 14 percent higher loads than the initial yield loads for Specimen 2 and Specimen 7 in Figures 12 and 4, respectively. The post-yielding linearity depends on the degree of strain incompatibility.

CONCLUSIONS

1. Fully filled concrete decks were found to be about 2.5 times stiffer than the comparable open steel grid deck.
2. Concrete-filled grid decks with a 2⅛-in. overlay were about 2.75 times stiffer than the fully filled decks.
3. Concrete is found to be ineffective in the tension zone.
4. The observed strain incompatibility between main bars and concrete is two to four times in all new concrete-filled decks. However, better strain compatibility is noted in an overlaid deck through experimental results.
5. Good strain compatibility is observed in old concrete-filled decks that were in service for several years.
6. Concrete-filled grid decks stiffened by the wide-flange steel stringers are 1.5 to 2.25 times stiffer than the stringer

stiffness alone. For example, full composite action between filled decks and steel stringers can be assumed for design purposes.

7. Fully filled grid decks show some linearity beyond the local main bar yielding, which emphasizes the hyperstatic nature of concrete-filled grid decks.

8. Ultimate concrete compression strains (0.003) were attained only in overlaid concrete-filled decks. However, poor strain compatibility between concrete and steel in other new decks occurred even though yielding of steel was noted; concrete and steel grid decks cannot be treated in unison for design purposes.

9. Deflection and moments of concrete-filled decks obtained from the orthotropic plate theory compared well with the experimental results.

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