Behavior of Open Steel Grid Decks Under Static and Fatigue Loads

HOTA V. S. GANGARAO, WILLIAM SEIFERT, AND HAGOP KEVORK

Open steel grid decks are factory assembled, lightweight, and easy to install. They are commonly used to rehabilitate older bridges by being welded to stringers, floor beams, or both. The American Association of State Highway and Transportation Officials (AASHTO) load distribution procedures for open steel grid decks are found to be in error; hence realistic load distribution procedures have been developed to prevent cracking of grid deck bars and plug welds. The research work presented here, however, deals only with the effects of main-bar spacing, direction of main bars with respect to traffic flow, load position, composite action, fatigue effects due to repetitive loads and residual stress build-up in grids during fabrication, braking and accelerating forces, galvanization, and composite action between the deck and stringer. Twenty-six grid deck specimens were tested under static and fatigue loads. Reduction in bending stresses due to composite action is found to be marginal. Allowable fatigue stresses for commercially available welded grid decks are found to be very close to those given for Category E in the AASHTO specifications. However, heavy-duty welded grid decks subjected to fatigue loads have developed no welded cracks after up to 1.5 million cycles. Under fatigue, riveted decks have performed better than the most common welded decks. Finally, welded decks that have been galvanized have a longer service life than decks without galvanization.

The rehabilitation or replacement cost of bridges in the United States is estimated to be about $50 billion in 1982 dollars (*1*). One of the most economical ways to increase the load-carrying capacity of a bridge and improve its safety is to rehabilitate the bridge deck with an open steel grid deck system. An open steel grid deck is factory assembled and consists of main and cross bars positioned so that they are perpendicular to each other and mechanically interlocked and plug welded, or riveted, at their intersections (Figures 1 and 2). Occasionally diagonal bars are added to produce a grid of higher stiffness in its plane.

The successful use of open grid decks can be attributed to their light weight (approximately 16 psf), ease of installation, decreased construction costs, ease of adaptability to the composite mode of construction, and use as temporary bridges or even as decking on movable bridges (*2*). Typically, open steel grid decks are welded to their stiffening system, usually wide-flange stringers, floor beams, or both. Because of increases in traffic intensity as well as in volume, open steel grid decks develop cracking of plug welds, which eventually leads to the failure of cross or main bars. Such failures are primarily attributed to poor design, which is the result of lack of understanding of the behavior of grid decks under static and fatigue loads. The current specifications for bridges from the American Association of State Highway and Transportation Officials (AASHTO) (*3*) suggest design procedures to determine both the distribution of wheel loads within an open grid deck and the distribution between the deck and its stiffening system. As discussed in the literature (*2, 4, 5*), design procedures consider only the stringer spacing and the number of traffic lanes. They do not account for other parameters such as stringer stiffness and spacing, deck stiffness, span length, composite action, fatigue behavior, and load location. Also, the AASHTO load distribution procedures for open grid decks (*3*) are in error in that they lead to a decrease in load intensity on the main bar as the main-bar spacing increases (*2, 6*). Hence, more realistic load distribution formulas have been developed by the authors to adequately design open grid decks for static and fatigue loads and to improve their service life. These distribution formulas are of two types: within an open steel grid deck and between the grid deck and steel stringer.

The major objective of this research paper is to present details on the behavior of open steel grid decks under static and fatigue loads so that designers can have a more complete understanding of the overall performance of the grid deck, which would lead to reduced maintenance costs. More specifically, research work is presented that evaluates deck performance with reference to main-bar spacing, direction of main bars with respect to traffic, braking-force effects, load range, composite action of the deck, type of deck, galvanization, effects of residual stress, static performance after fatigue loading, and load influence on adjacent panels.

A comprehensive experimental testing program has been devised and the aforementioned problem parameters have been varied in a systematic manner to study their influence on the overall behavior of grid decks. The scope of this paper is limited to the behavior of open steel grid decks under static and fatigue loads. The design formulas derived from the information gained during this research are presented in a separate paper for the sake of clarity and brevity. More comprehensive details on both the behavior and design equations may be found in the final report, available from the West Virginia Department of Highways or Bridge Flooring Manufacturers Association of Pittsburgh, Pennsylvania (*7*).

Civil Engineering Department, West Virginia University, Morgantown, W. Va. 26506-6101.

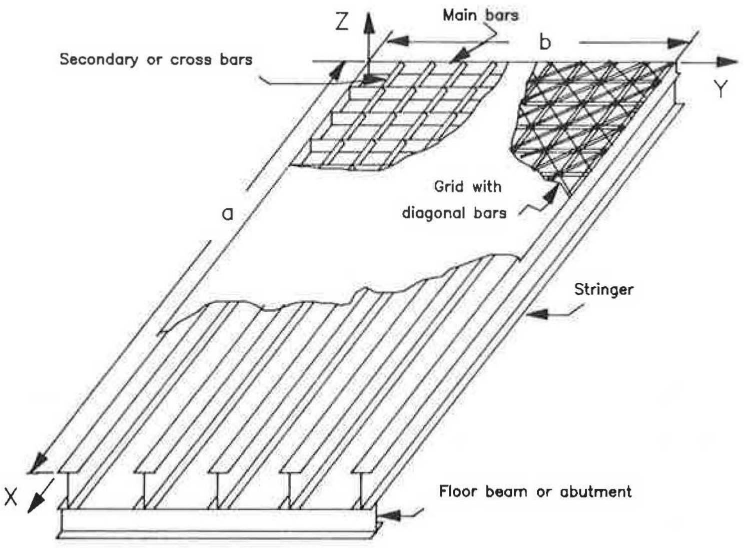


FIGURE 1 Open-deck–wide-flange stringer bridge system.

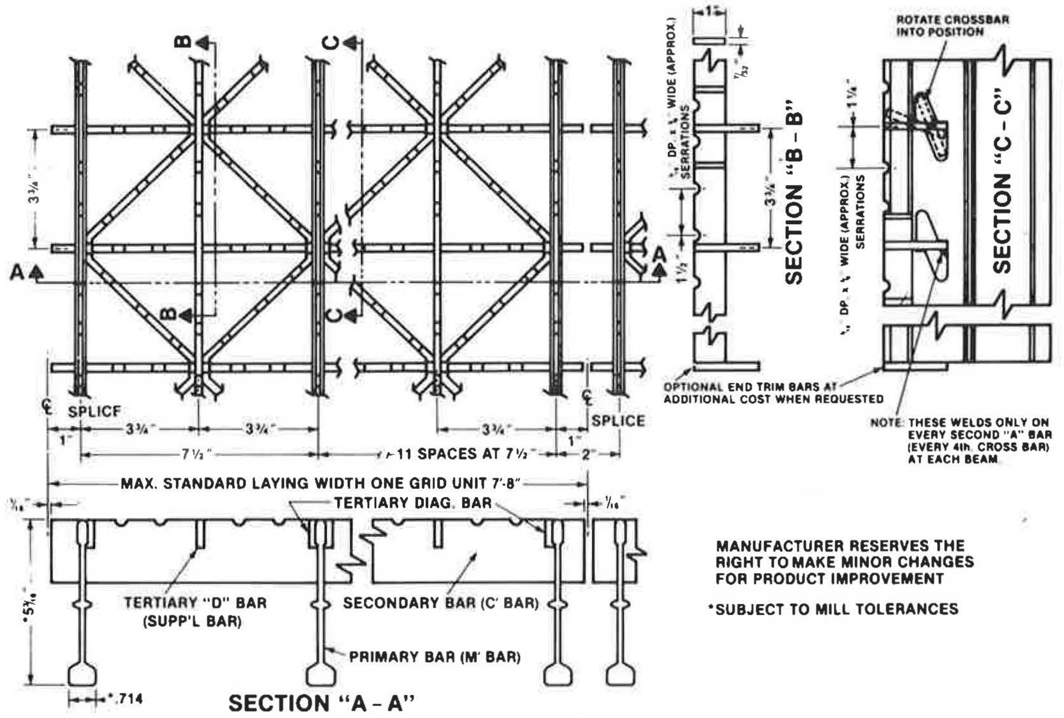
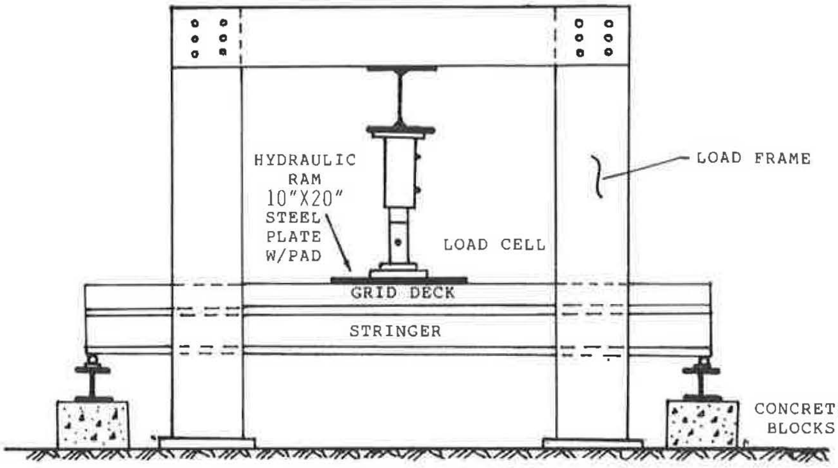


FIGURE 2 Diagonal open grid deck details.

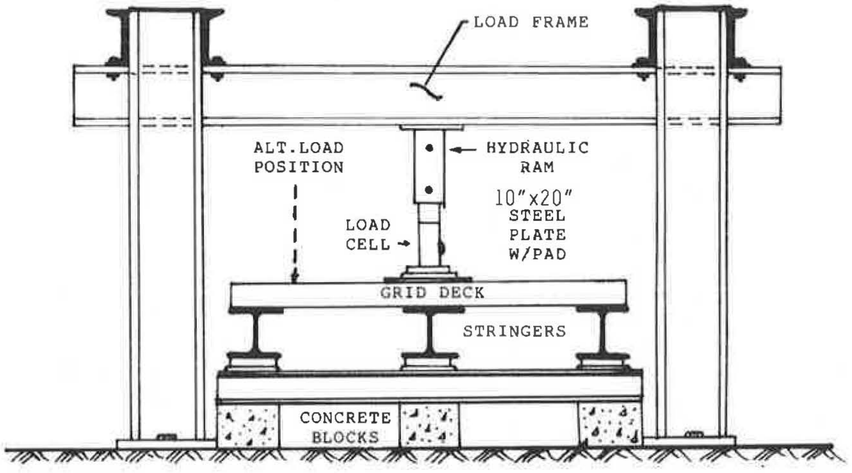
TEST SETUP AND SPECIMEN TESTING

A schematic diagram of a typical test setup is shown in Figure 3. A typical setup consists of an open grid deck placed over steel stringers and stiffened by steel floor beams. The floor beams are supported on concrete blocks, which are placed directly under each stringer. The load was applied through a hydraulic ram for static tests and through a closed-loop MTS actuator for fatigue tests. The loading was spread over a 10- by 20-in. area of the grid deck with steel plate and elastomeric pad for proper simulation of dual wheel loads. Some experiments were conducted by using a wedge effect on the actuator or ram to simulate the in-plane forces due to braking or accelerating of trucks on grid decks. The grid decks are welded either fully or partially to the stiffening system to study their composite behavior. Additional details are given in the final report (*7*).

Three typical specimen sizes (6 by 10 ft, 16 by 7.58 ft, and 6 by 24 ft) are used in the tests for static and fatigue loads. To date, a total of 26 different static and fatigue tests have been conducted on various commercially available grid decks (diagonal and riveted decks with main-bar spacing of 4, 6, and 8 in., and a 5-in., four-way grid deck). These open grid deck specimens were randomly chosen from the general stockpile and were not specifically fabricated for the test purposes. The



FRONT VIEW



SIDE VIEW

FIGURE 3 Typical test setup.

5-in., four-way grid deck was introduced on the basis that in-plane force resistance and rideability would be better with this grid than they are with the rectangular grids. However, it was not recognized that the concentrated force transfer from the diagonal bars to the center of the cross bars would be detrimental to the fatigue resistance.

Static tests on each panel were conducted by applying incremental loading from 0 to 30 kips, whereas fatigue tests were performed with the aid of a 50-kip capacity MTS system with stress ranges from 8 to 37.8 ksi and a maximum of 1.5 million cycles. It should be noted that static tests were performed on specimens subjected to repetitive loads at the end of every 50,000 cycles to measure the specimen degradation due to fatigue cracking.

Strain and dial gauges were mounted at several locations on grid decks and also on stringers and floor beams. In addition, residual stresses in the grid decks were measured through a strain relief test devised and perfected by the authors (*7*).

TEST RESULTS AND SYNTHESIS

Static and fatigue tests of open steel grid decks stiffened by steel stringers were performed in the Major Units Laboratory of the Civil Engineering Department at West Virginia University. The effects of 10 different variables were systematically researched for steel grid decks under static and fatigue loads. These variables are main-bar spacing, traffic flow with main-bar direction, braking force effects, range of applied loads, composite action of grid deck and steel stringers, type of deck, galvanization, residual and induced stress effects, static versus fatigue behavior, and applied load influence on adjacent grid panels.

Main-Bar Spacing

Test results of grid decks with main-bar spacing of 4, 6, 7½, and 8 in. revealed that deck deflections and main-bar stresses increased with spacing. The variation in deflections and stresses is shown in Table 1. The data indicate that stiffness of open grid decks decreases with increases in main-bar spacing.

Traffic Flow with Main-Bar Direction

Varying the direction of traffic with respect to the main bars on a grid deck–stringer system revealed no significant variation in

TABLE 1 STRESSES AND DEFLECTIONS CORRESPONDING TO 20-KIP LOAD

Main-Bar Spacing (in.)	Stresses on Main Bar (ksi)		Deflection of Main Bar (in.)
	Top	Bottom	
4	13.8	12.9	0.108
6	25.0	19.6	0.116
7.5[a]	20.8	21.3	0.128
8	27.2	19.4	0.157

NOTE: The open grid flooring consisted of commercially available panels fabricated from ASTM A 588 steel with allowable steel stress *fs* of 27 ksi. This value was suggested by the manufacturers (Greulich, Inc., Belleville, N.J.). Properties of main bars whose spacing is 4, 6, and 8 in.:

Weight = 6.09 lb/ft; $I = 5.108$ in.^{4}; depth = 5.196 in. (see Figure 2); cross-bar and supplementary-bar sizes are $2 \times {}^{1}/_{4}$ in. and $1 \times {}^{5}/_{16}$ in., respectively.

Properties of main bars whose spacing is 7.5 in. (5-in., four-way grid):

Weight = 4.83 lb/ft; $I = 4.137$ in.^{4}; depth = 5.188 in.; cross-bar, supplementary-bar, and diagonal-bar sizes are $2{}^{1}/_{16} \times {}^{13}/_{64}$ in., $1 \times {}^{7}/_{32}$ in., and $1 \times {}^{7}/_{32}$ in.

Additional details of open steel grid deck panels are shown in Figure 2, and other design information can be obtained from the manufacturer's catalogs, which can be obtained from the Bridge Grid Flooring Manufacturers Association, 231 South Church Street, Mount Pleasant, Pa. 15666.

[a] Bending stresses and deflections increase with increases in bar spacing except when the main-bar spacing is 7.5 in. This grid deck has diagonal bars and supplementary bars that alter the load distribution within the deck. For additional explanations, see final report (*7*).

deflection. However, moment variations in the main bars of a 4-in. spaced deck were found to be about 11 percent for two identical grid decks, one set up with main bars parallel to and another with main bars perpendicular to traffic (see Table 2). Such a difference in moments is attributed to the presence of five main bars under the load in the parallel direction and only two in the perpendicular direction. Typically, strain and deflection measurements tend to be larger when the main bars are perpendicular to the traffic flow than when the main bars are parallel to the traffic flow.

Braking Force Effects

Braking or accelerating forces were simulated in the laboratory by using a wedge under the wheel load that transfers a portion of the applied vertical load in the plane of the grid. When in-plane forces act along the length of the main bar, they induce compressive stresses that are superimposed on compressive stresses induced from vertical wheel loads. However, if braking forces are perpendicular to the main bars, they dissipate a portion of the main-bar stress, and in this case, in-plane compressive forces are induced on a portion of the top of the cross bars. Similarly, tensile forces are induced on other portions of the cross bars. Therefore, the critical wheel load position is when the traffic is parallel to the cross bars, because these are found to be most vulnerable to failure under fatigue-induced loads. The design equations developed reflect this critical load position.

Range of Applied Loads

The fatigue life (number of cycles) in the case of constant amplitude load testing decreases with an increase in bending stress range. This can be found from the results given in Table 3. Commercially available grid decks subjected to fatigue loads showed no crack propagation at stress ranges below 10 ksi. The most significant factor controlling fatigue life of a welded grid deck is the spacing of the main bars; for example, the fatigue life of a deck with 4-in. main-bar spacing was 700,000 cycles versus 500,000 cycles for a deck with 6-in. main-bar spacing. All the fatigue cracks were formed at the tops of the cross bars. The cracks were perpendicular to the longitudinal direction of the cross bars and very close to the main- and cross-bar junctions. This implies that bending stress on cross bars is the predominant factor in the fatigue failure of grid decks. The cross bar does not have a uniform cross section because of notches; thus, these experiments revealed that the effective moment of inertia is based on only 70 percent of total height.

The standard bending stress range of cross bars versus the number of cycles (*S-N* curves on a log-log scale) for welded grid decks was developed on the basis of the experimental information derived from this study. From these test results, it is concluded that a welded grid deck system (excluding 5-in., four-way grids) stiffened by being welded to stringers, floor beams, or both can be classified under Category E of the AASHTO specifications (see Figure 4). The controlling factor is the bending stress range of the grid cross bars subjected to a typical truck load, in which the transverse load distribution factor has to be determined in accordance with the formula developed by the authors (*7*).

TABLE 2 EFFECT OF DIRECTION OF TRAFFIC WITH RESPECT TO MAIN BARS

Bridge Component	Main-Bar Spacing (in.)	Moment (kip·in.) by Direction of Traffic		Deflection (in.) by Direction of Traffic	
		Parallel to Main Bars	Perpendicular to Main Bars	Parallel to Main Bars	Perpendicular to Main Bars
Main bar	4	23.78	26.79	0.100	0.104
Cross bar	6	5.07	5.07	0.298	0.299
Stringer	6	398.05	398.05	0.174	0.178

NOTE: The 20-kip load is positioned at midspan and centered between the stringers. Moments are computed from the strain readings. The change in direction of traffic from parallel to perpendicular is simulated by rotating the 10 × 20-in. loading plate over a 90 degree angle. All cross bars ($2 \times {}^{1}/_{4}$ in.) have a center-to-center distance of 4 in.

TABLE 3 STRESS RANGE VERSUS FATIGUE LIFE

Main-Bar Spacing (in.)	Constant Amplitude Stress Range (ksi)	Fatigue Life (cycles to failure)
6	15.4	500,000
4	13.5	700,000
4	11.4	750,000
4	8.5	1.5×10^6

NOTE: All fatigue tests are performed on 6- × 10-ft open steel grid decks stiffened by three W10×22 stringers, two at the ends and one in the middle with 5-ft spacing. Frequency of fatigue load is 1.6 Hz. A dual tire loading is simulated over an area of 10 × 20 in. and is applied by means of a 0.5-in.-thick steel plate and elastomeric rubber pad.

A more realistic approach in designing a welded grid deck for fatigue resistance is to properly account for residual stress effects as well as induced stresses (see section headed Residual and Induced Stress Effects), which are due to differential elevation between stringers or curvature variations within a grid deck. The authors found that if the vertical axis of the *S-N* curve is represented by a log value of the maximum stress (maximum stress in a member from applied loads plus residual stress, which varies with bar spacing and pattern, plus induced stresses), the design *S-N* curve for welded decks has to be classified as Category A (see Figure 4). Once again, the test data were extensively synthesized before this conclusion was derived; additional information may be found in the final report (7). From the design viewpoint, it would be ideal to shim the gaps between the grid deck and the stringers over the full stringer flange width before welding. If the deck is not properly supported by stringers or is forced down for welding, the induced stress will be high and detrimental to service life.

Composite Action of Grid Deck and Steel Stringers

Before presentation of the details on composite action, it should be noted that the term "composite action" in this paper always refers to the effect of the grid deck on a supporting stringer that is transverse to the main bar of the grid deck. Results in Table 4 indicate that, under static loads, a maximum increase of about 8 percent in the composite action of the grid deck–stringer system is observed when every fourth main bar is welded to the stringers as compared with the noncomposite deck–stringer system. However, other results in Table 4 indicate that there is no significant increase in composite action when every second bar is welded to the stringers instead of every fourth bar. Hence, it would be economical to weld only every fourth bar. Two identical decks were tested under identical fatigue loads; one deck has a noncomposite system and the other has every fourth main bar welded to the stringers. At the end of a million fatigue cycles, the noncomposite deck lost twice as much stiffness as the deck that was sparsely welded to the stringers, which leads to the conclusion that deck service life under fatigue improves when the deck is welded to the stringers.

Type of Deck

Load deformation tests were performed on welded as well as riveted decks. No fatigue failure was observed on riveted decks even after they were subjected to 1.5 million cycles. This may be attributed to frictional damping in riveted decks. Nevertheless, crack initiation takes place in most welded decks at about 400,000 to 500,000 cycles at high stress ranges because of high stress concentrations or stress raisers near reentrant angles, residual stress buildup during fabrication, and large openings in main bars. However, riveted decks are found to be more flexible than welded decks. This is attributed to excessive slack in a riveted deck system.

Galvanization

Two identical grid decks (with and without galvanization) were tested under identical fatigue load ranges. A fatigue life of 1 million cycles was observed for galvanized decks, whereas 700,000 cycles was noted for nongalvanized decks. A similar improved service life in galvanized decks was noted through field observations (personal communication, Ackrow Corporation, April 1987). Furthermore, a 10 percent variation in main-bar stresses was noted at the top of the deck with

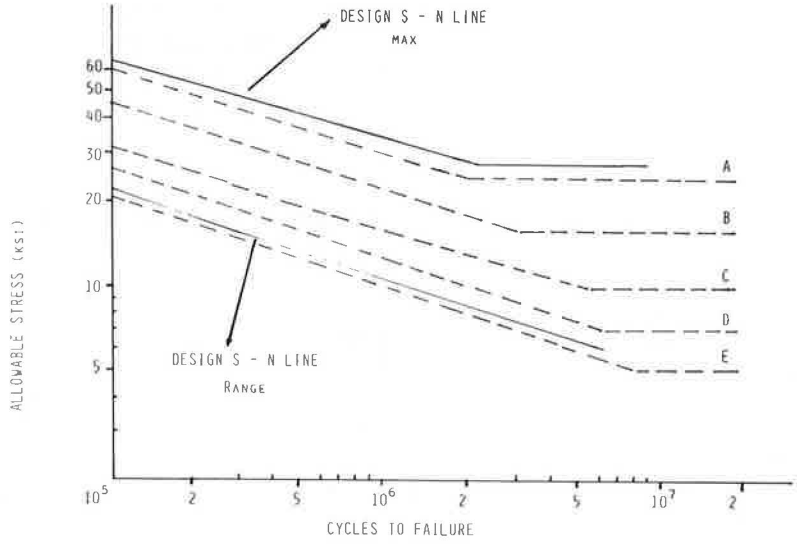


FIGURE 4 Design *S–N* lines for open steel grid decks.

TABLE 4 COMPOSITE ACTION

Type	Load (kips)	Deflection (in.)
Every fourth bar welded[a]	20	0.314
Every second bar welded[a]	20	0.306
Noncomposite[b]	20	0.133
Composite with every fourth bar welded[b]	20	0.122

[a] Dial gauge directly under load on main bar. Test specimen 16 by 7.58 ft. with 6-in. main-bar spacing.
[b] Dial gauge directly under load on main bar. Test specimen 6 by 10 ft with 4-in. main-bar spacing. Test grid loaded at middle of two consecutive stringers.

identical stress at the bottom. This may be due to residual stress relief at the top of the deck during the galvanization process, which consists of heating to 860°F and cooling to ambient temperatures.

Residual and Induced Stress Effects

Residual Stresses

Residual stresses in welded joints result primarily from shrinkage due to cooling. These joints are restrained by adjacent parts that have not been heated to high temperatures (1700° to 1800°F). The effects of welding-induced residual stress in open grids are substantial. Residual stresses in grid decks were measured in the laboratory by using electrical strain gauges to observe the decrease in strain (and consequently stress) after the removal of a welded joint connecting the main and cross bars. Because the residual stresses are localized at regions surrounding the weld joints, the removal of such a region should relieve the stresses in the remaining main and cross bars. The magnitude of residual stress in grid decks was measured to be as high as 27 ksi, even though some scatter was noted in the experimental data. The residual stresses were found to be higher for decks with closer main-bar spacing. However, for 5-in., four-way grid decks, residual stresses are lower because of the better in-plane stress distribution provided by diagonal bars. Similarly, galvanized decks have lower residual stresses than nongalvanized decks.

Induced Stresses

Grid decks are often not in full contact with top flanges of supporting stringers because of differential elevations of stringers or warping of grids during fabrication. According to the AASHTO specifications, the grid deck should be forced down and welded to the top flange of the stringer or floor beam. Laboratory testing of a commercially available grid deck with 6-in. main-bar spacing and a 3/4-in. differential elevation over a 6-ft stringer spacing revealed an induced main-bar stress of 17.3 ksi. This clearly proved that induced stress can be very high under typical field conditions and may create adverse effects on grid deck performance.

Static Versus Fatigue Behavior

Test results have shown conclusively that grid deck stiffness decreases with the increase in number of cycles. However, test results revealed that fatigue has no significant effect on welds between the deck and the stringers. This proves that fatigue is a local problem in open steel grid decks. The cross bars do not rest fully on the main bars, and plug welds are not structural welds. Hence, the deck does not act like a perfect plate (less than 100 percent torsional moment transfer). The deck is subjected to relative movement of bars at main- and cross-bar junctions and also is free to move at the bottom of the cross bars because of oversized notching in the main bars for fabrication purposes. This leads to additional slackness in the deck system.

Applied Load Influence on Adjacent Grid Panels

Strain measurements were taken on all panels of the grid deck that are continuous over the stringers, whereas the loading was applied on one panel only. Test results revealed that the strain and deflection effects of the load on an adjacent panel were no more than 8 percent of the strain or deflection on the loaded panel. Also, strain relief on the adjacent panel over the full fatigue life of a deck is insignificant. This is a very significant observation in the case of structures subjected to moving loads. It implies that the interaction of loads from adjacent panels is insignificant and that a deck can be designed on the basis of average daily truck traffic only, without incorporating the influence of trucks on contiguous deck panels in the deck design.

A significant amount of research work has been carried out to develop theoretical and design equations for load distribution, displacements, and moments in steel grid decks stiffened by a stringer-and-diaphragm system. That work and a large volume of experimental and theoretical data are not reported here because of space limitations. It should be noted, however, that the experimental and theoretical correlations are found to be excellent; they are reported elsewhere (*7*).

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn on the basis of the experimental program on open steel grid decks:

1. Reduction in bending stresses due to composite action is found to be a maximum of 8 percent when the applied load is between stringers or at any general location.
2. Moments of a grid deck–stringer system are lower by about 11 percent when main bars are parallel to traffic rather than perpendicular to traffic.
3. Laboratory results indicate that the stresses and deflections of a grid deck–stringer system are lower when the main bars are parallel to the traffic. Furthermore, main-bar direction should be such that braking or accelerating forces are parallel to the main bars, to avoid additional compressive stresses on the cross bars.
4. Field-induced stresses can be very high (approximately 30 ksi), and the practice of forcing the deck to the stringer and welding it in place should be avoided.

5. Residual stresses obtained experimentally by material removal tests are found to be considerable (approximately 27 ksi), and they seem to have a direct effect in reducing the fatigue life of a deck.

6. Fatigue life (number of cycles before cracking of plug welds) decreased with the increase in main-bar spacing and the increase in stress ranges. An open welded grid deck system (except 5-in., four-way diagonal grids) can be classified under AASHTO Category E with no field-induced stresses if the stress range is considered to be the vertical-axis parameter. However, a more realistic approach, which covers all types of grid decks and all the construction details, is to classify a grid deck under AASHTO Category A by altering the vertical-axis parameter to maximum stress, that is, the sum of maximum stress from applied loads, residual stresses in a grid, and induced stresses in the field.

7. Galvanized welded grid decks have a longer service life than nongalvanized decks, which is attributed to the stress relief caused by the galvanization process.

8. Riveted decks have a longer fatigue life for many reasons, for example, fewer stress raisers, frictional damping, and higher flexibility at junctions of the main and cross bars.

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