Bolted Connections of Rib-Plate Structures

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A field study of an aluminum box culvert subjected to backfill and live load is correlated with a laboratory load testing of a rib-reinforced plate. Stress concentration and distribution of stress are examined in the region where bolts connect reinforcing ribs to the corrugated plate. Moments and thrusts on ribs and plates are computed to examine composite behavior. Stresses in the region of bolts that attach ribs to the corrugated plate are only in approximate agreement with results obtained from the finite-element computer program CANDE. Experimental data suggest that plate distortion near the assembly bolts results in local bending stresses. Field measurements show that rib and plate forces act as noncomposite members during backfilling, but respond compositely with the application of live load. A flat, corrugated plate with no-rib, one-rib, and two-rib combinations was tested in the laboratory under a concentrated load acting at the center and a constant bending moment. Stresses were found to have significant variations perpendicular to the corrugations that may be corrected with a shift in the neutral axis. Stresses are in agreement with the constant ratio of composite response for the rib and corrugated plate when stresses are measured between bolts. Stress concentrations and local distortions at rib ends were duplicated in the laboratory.

A number of investigators have tested culverts with reinforced ribs. The normal procedure has been to assume composite action and to neglect thrust forces. This paper extends previous work on these assumptions and also examines shear transfer at the bolted connection. One mode of failure anticipated on these culverts is failure of the bolt connections (Figure 1); understanding connections is the key to increasing the efficiency of these structures.

Box culverts are assembled by bolting together curved, corrugated metal plates. Rib stiffeners are often used to increase the flexural stiffness and moment capacity of the plate. These stiffeners, curved to conform to the shape of the culvert, are bolted to the corrugated plate at intervals spaced along the length of the culvert. The ribs are spaced to support maximum applied moments and so do not extend to the foundation. The reinforced design permits the use of culverts at locations of shallow covers. Despite the use of reinforcing ribs, the stiffened structures are quite flexible, so the backfill must be good quality soil and properly compacted.

During the backfill process lateral soil pressure moves the sides of the culvert inward and the crown upward, a phenomenon known as *peaking*. Once the backfill has been placed to crown level, subsequent backfill placements reverse this trend by pressing the crown downward and the sides outward. Similarly, when the live load is applied, the structure deflects downward at the top and outward at the sides.

A number of studies have compared field measurements with finite-element solutions or design standards. The results from several of these studies are useful in examining composite action and local stress variations. Duncan (*1*) made an in-depth study of the interaction between flexible metal culverts and the surrounding backfill for both shallow and deep-cover conditions using field data and finite-element analyses. In a more recent study, Duncan (*2*) investigated the behavior of an aluminum box-type culvert with electric strain gauges attached to the haunch and the crown. Comparisons of the experimental data with the finite-element analysis indicate that moments in the crown are likely to be the same, but moments in the haunch are likely to be appreciably smaller than design moments.

In a research project, Beal (*3*) instrumented an aluminum box culvert at the crown and haunches with strain gauges and curvature-measuring devices. The data analysis used to convert measured strains to bending moments was modified to account for the degree of composite action between the plate and the rib, thus allowing the calculation of bending moment independent of the thrust. Beal reasoned that the magnitude of thrust in a low-cover culvert is small and can be neglected. In another research project, Beal (*4*) instrumented an aluminum structural plate culvert at 16 locations spaced around the structure. Beal made several observations that are useful when instrumenting ribbed aluminum culverts:

1. Gauges mounted on the plate located directly under the ribs did not give reliable estimates of average plate strain,
2. The backfill placement sequence resulted in distortion of the culvert shape, and
3. Live load stresses were small compared with backfill load stresses.

INSTRUMENTATION

This study consisted of a field investigation coordinated with a laboratory study. The field study was conducted on an aluminum box culvert installed under State Route 269 in Noble County, Ohio. The rib-plate structure had a 14-ft, 10-in. span, 4-ft, 10-in. rise, and was 42 ft long with concrete headwalls.

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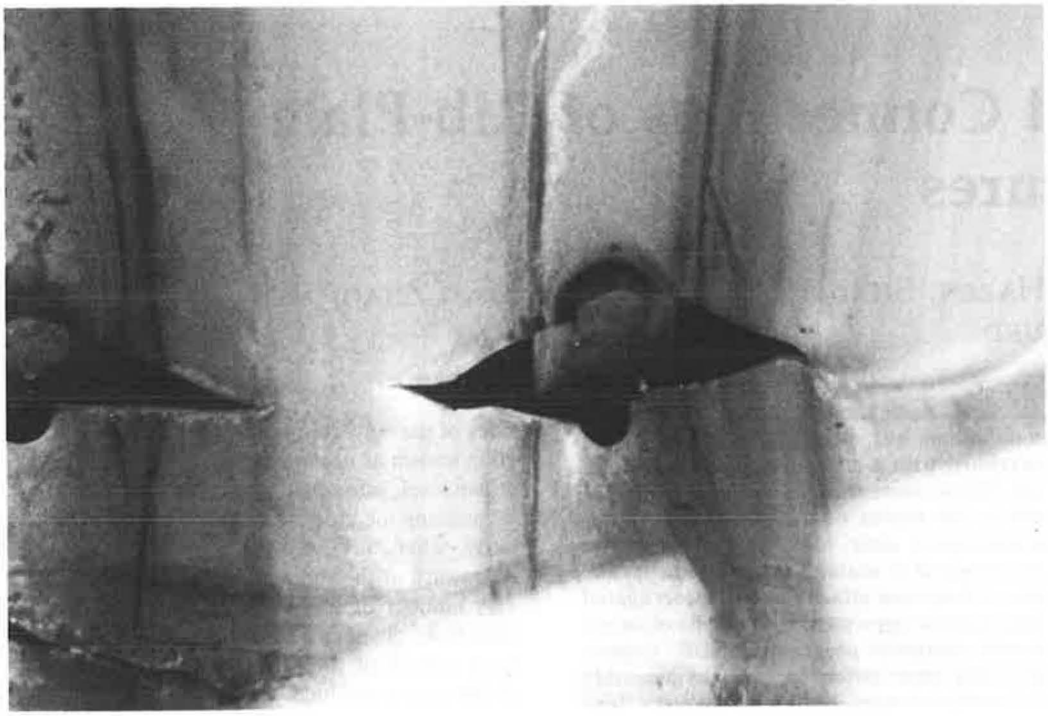

FIGURE 1 Failed box culvert. (Cross section located at the end of side rib.)

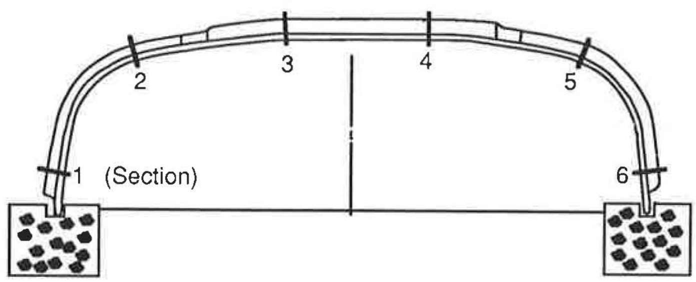

FIGURE 2 Location of instrumented sections.

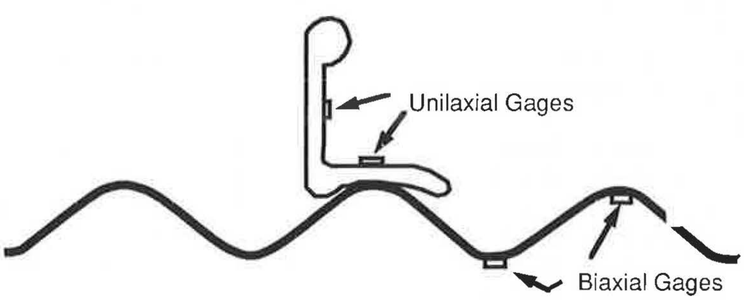

FIGURE 3 Typical location of strain gauges.

The ends of the corrugated plate were embedded in 3- by 3-ft concrete strip footings. The cross section of the structure is shown in Figure 2. Ribs were bolted to the structure as shown in Figures 2 through 5. The top ribs were spaced on 18-inch centers, whereas the side ribs were spaced every 27 inches. Sections 1 through 6 were instrumented with strain gauges to determine the bending moments and thrusts on these sections, as shown in Figures 2 and 3. At each section, two uniaxial electric strain gauges were attached to the outside rib and two biaxial strain gauges were attached to the inside corrugated plate. Biaxial gauges mounted on the plate were located one corrugation from the rib in order to move away

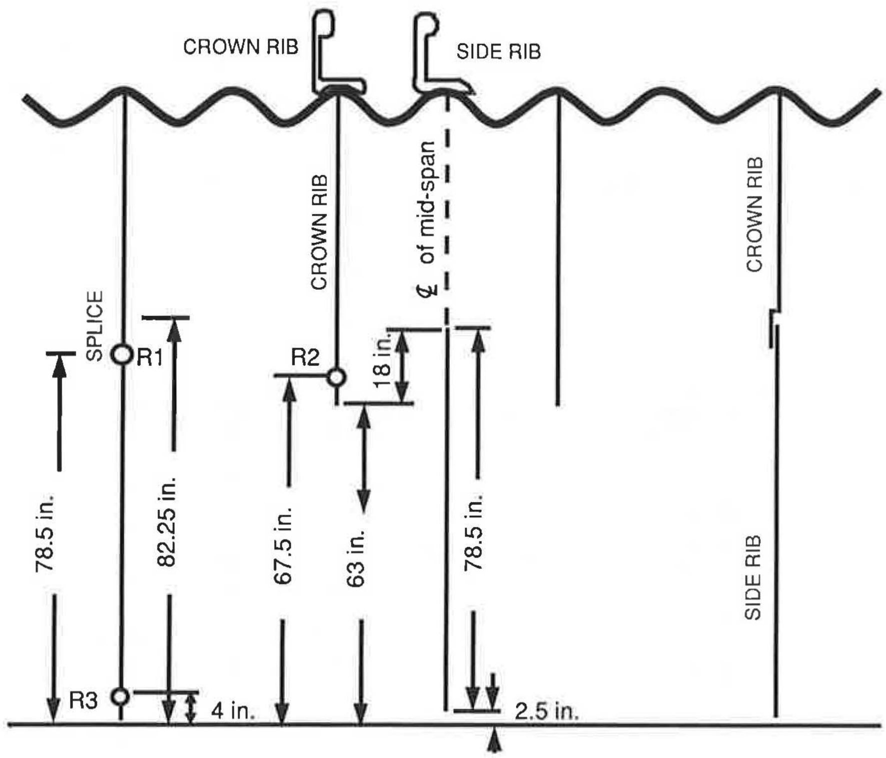

FIGURE 4 Location of rosette groups.

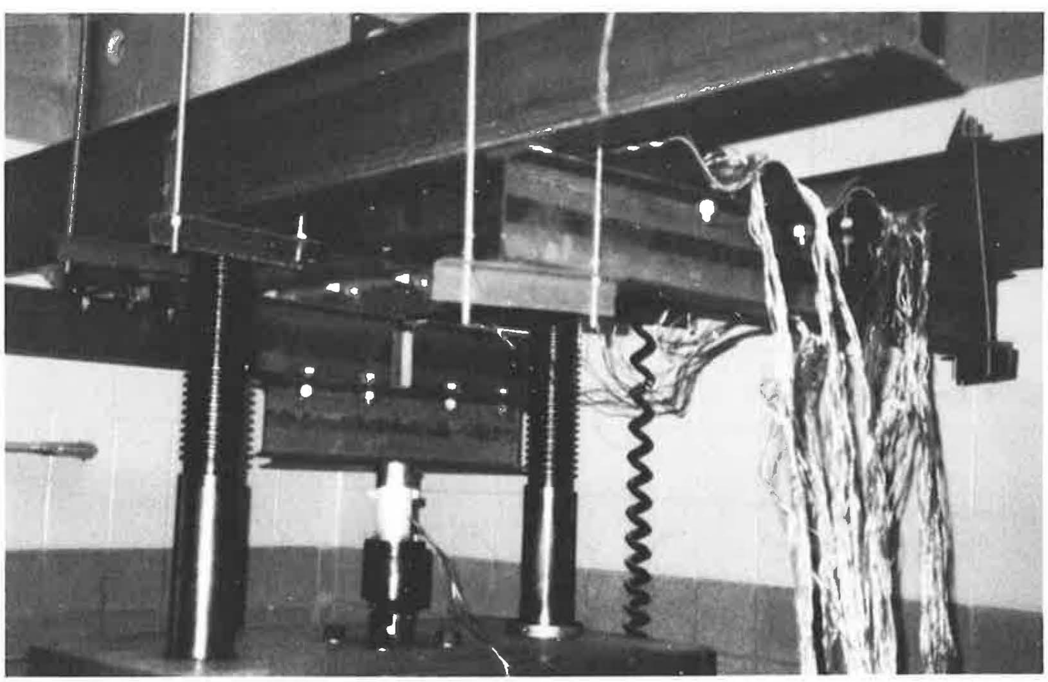

FIGURE 5 Laboratory loading apparatus.

from possible strain disruption. Electric strain gauge rosettes were placed in patterns at locations R_1, R_2, and R_3 as shown in Figure 5. Strain gauge rosettes were cemented along planes rotated 0°, 45°, and 90° to the longitudinal plane of the culvert. These patterns were located at the ends of reinforcing ribs because the local bending effect was expected to be large.

Before field testing, electric strain gauges were mounted on bending specimens. These gauges were tested for stability of readings under a variety of load levels and environments. Several recommended gauge protection systems were tested. All electric strain gauges installed were 350 ohms to minimize wire resistance. A powered bridge, three-wire reading system was used to read strain values. Data were recorded automatically in a computer, printed, and inspected visually as readings were taken.

A laboratory study was designed to examine field results in an environment that could be more closely monitored. Identical plate and crown ribs were obtained from the manufacturer and used in the laboratory study. Four sections across the rib-plate were instrumented for moment and thrust, and a bolt located at the rib end was instrumented to examine local stress concentration. The aluminum corrugated plate tested in the laboratory had a 6-ft, 10-in. span and a 2-ft, 3-in. width and was loaded with two sides free and the other two sides bolted to I-beams. Bags of granular fill were placed between a short I-beam and the plate crown. Corrugations provided side support to the bags of backfill so they would not split.

The test setup is shown in Figures 5 and 6. A constant moment and a concentrated center loading were applied to a

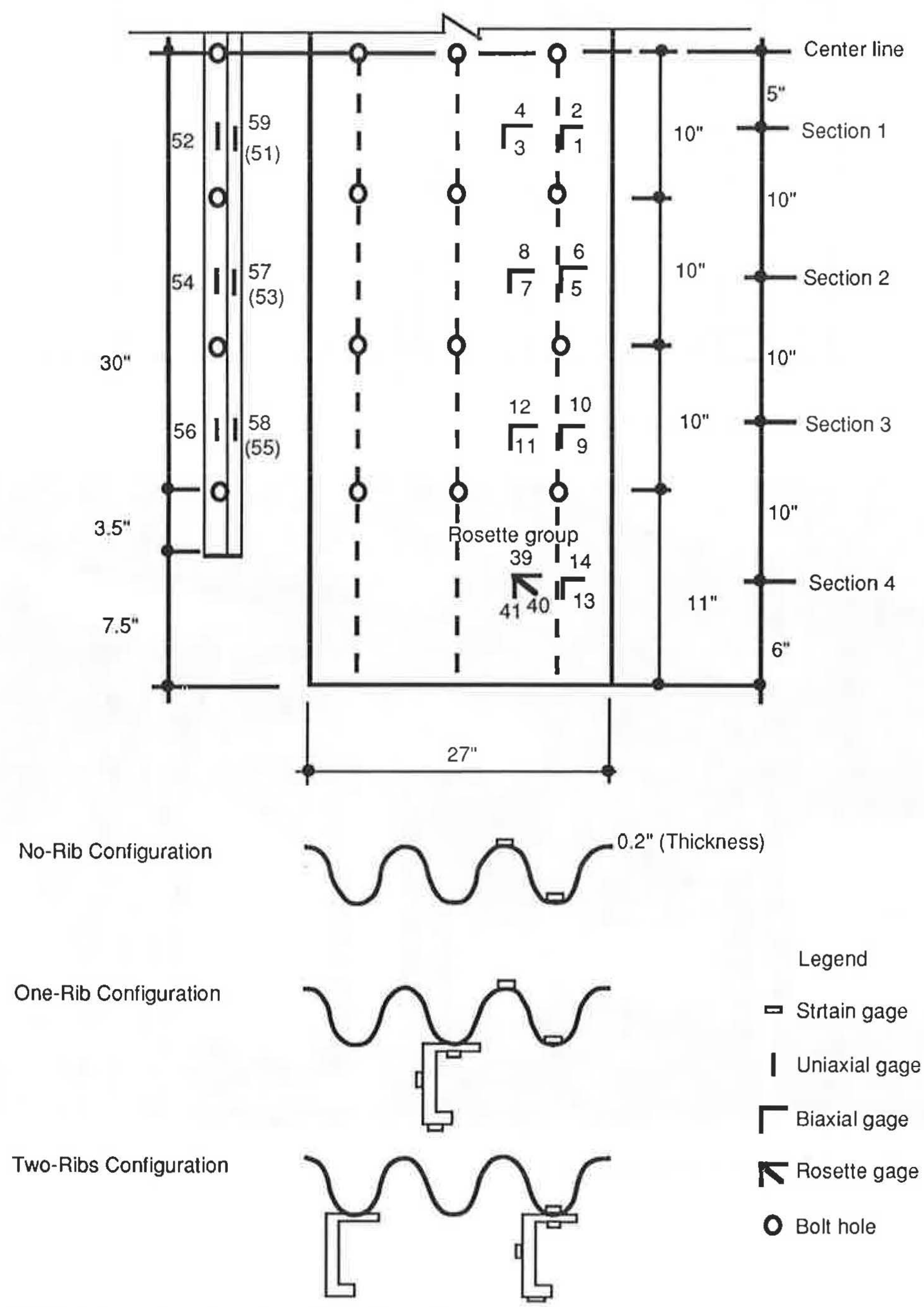

FIGURE 6 Laboratory plate-rib configurations.

no-rib, one-rib, and two-rib configuration. To duplicate field conditions, the ends of the plate were attached to an I-beam for all loading situations, as shown in Figure 5. The plate was mounted upside down to accommodate the loading frame. A concentrated center load was applied by the load piston to the plate center line. When a constant bending moment was applied, the load was applied symmetrically. All bolts were torqued to field specifications.

FIELD RESULTS FOR MOMENT AND THRUST UNDER LIVE LOAD

Bending moment and thrust forces in instrumented sections of the box culvert are shown in Figures 7 and 8. Noncomposite moments and thrusts were calculated from the four strain gauges shown in Figure 3. A linear response was assumed across the rib and across the plate. Thus, the moment was calculated as the sum of moment in the rib, moment in the plate, and moment resulting from the couple created by the rib thrust and the plate thrust. Composite moments and thrusts were calculated from only the two outside gauges. A linear response was assumed across the combined section. Thus, the moment was calculated directly. For initial backfilling, the agreement was not good between composite and noncomposite action. However, the assumption of composite action showed improvement with an increase in load and appeared to be good for 130 percent of H20 traffic load (42 kips).

Moment compared favorably with theoretical calculations, with maximum moments at the center and haunches of the

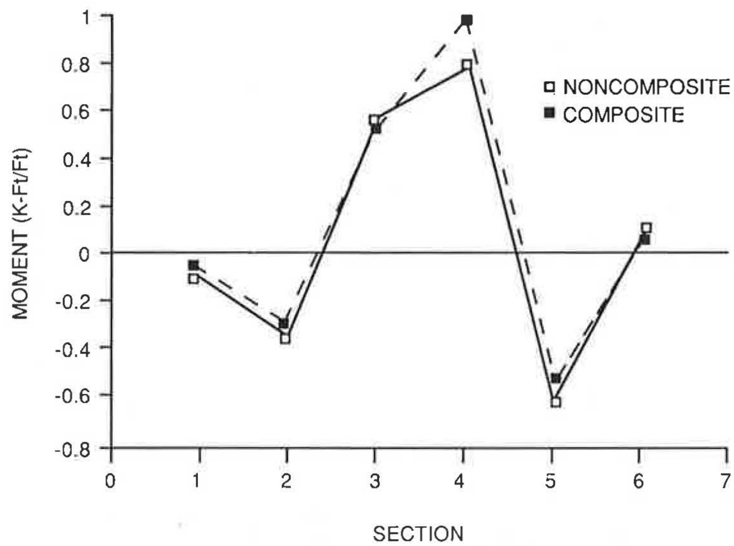

FIGURE 7 Moment comparisons with 42-kip live load at center position.

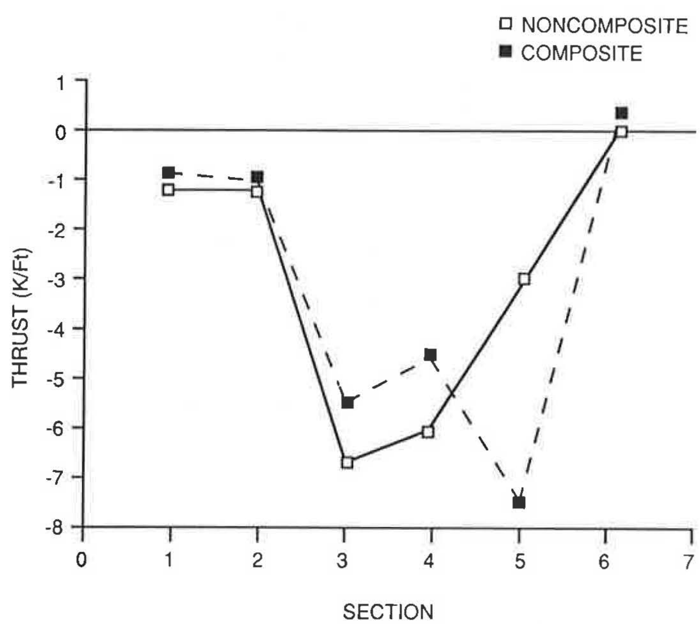

FIGURE 8 Thrust comparisons with 42-kip live load at center position.

culvert. Coupons were tested from both the plate and the rib. The moduli tested confirmed published moduli (5) of 10.2 × 10^3 ksi for plate 5052 and 10.0 × 10^3 ksi for plate 6061-T6. The proportional limit recorded was 27.5 ksi in the plate coupon. The experimental moment for all sections did not approach the plastic moment capacity of 13.72 k-ft/ft on the crown or 7.94 k-ft/ft on the side. Hence, plastic action was not a consideration. Thrust (Figure 8) accounts for an important share of the load-carrying capacity of the culvert, and thus cannot be neglected. Again, the thrusts compared well with composite response for live loading.

LABORATORY RESULTS FOR MOMENT

In the laboratory, composite moments (which were calculated with the procedure used for field data) compared poorly with theoretical values as shown in Figure 9. Moments calculated

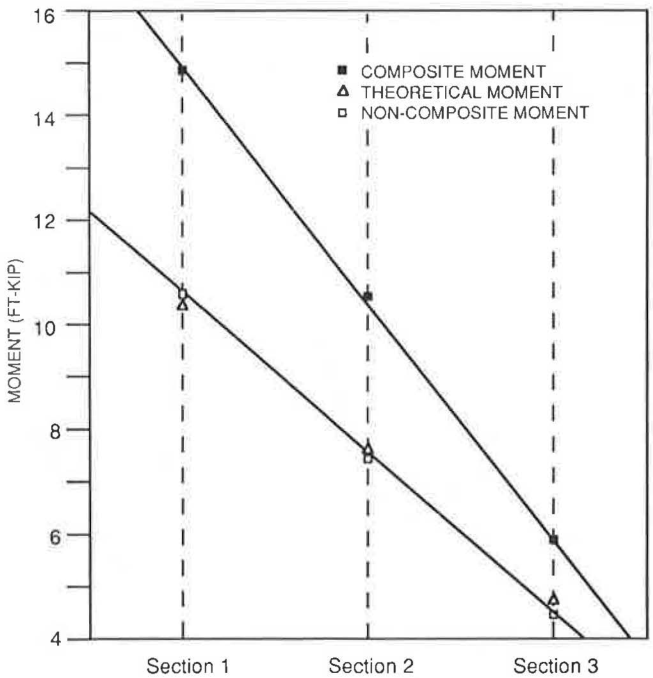

FIGURE 9 Laboratory moment comparison with concentrated center load of 7.43-kip, one-rib configuration.

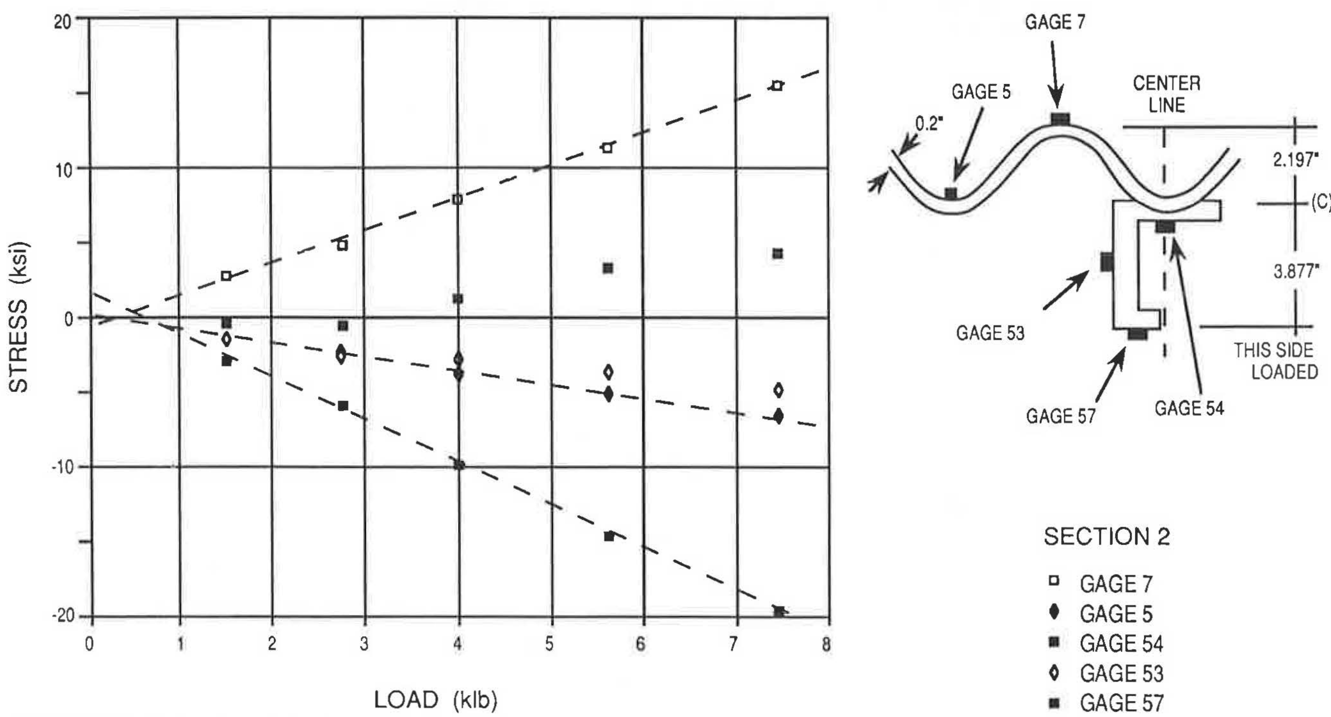

FIGURE 10 Laboratory test of center load, one-rib configuration.

TABLE 1 RATIO OF CROWN STRESS AND VALLEY STRESS IN CORRUGATION DIRECTION

Load	no rib center load			Load	no rib constant moment		
P	section 1	section 2	section 3	P	section 1	section 2	section 3
(kip)	$\|\sigma_3/\sigma_1\|$	$\|\sigma_7/\sigma_5\|$	$\|\sigma_{11}/\sigma_9\|$	(kip)	$\|\sigma_3/\sigma_1\|$	$\|\sigma_7/\sigma_5\|$	$\|\sigma_{11}/\sigma_9\|$
-0.53	1.62	1.63	1.59	-1.48	1.63	1.74	2.0
-0.90	1.64	1.64	1.56	-2.4	1.66	1.77	2.0
-1.52	1.62	1.62	1.54	-4.8	1.65	1.78	2.2
-2.12	1.62	1.63	1.54	-5.8	1.63	1.79	2.2
-2.86	1.62	1.63	1.57				
-3.01	1.62	1.63	1.58				

Note: σ_3, σ_7, σ_{11} are stresses at crown of corrugation.
σ_1, σ_5, σ_9 are stresses at valley of corrugation.

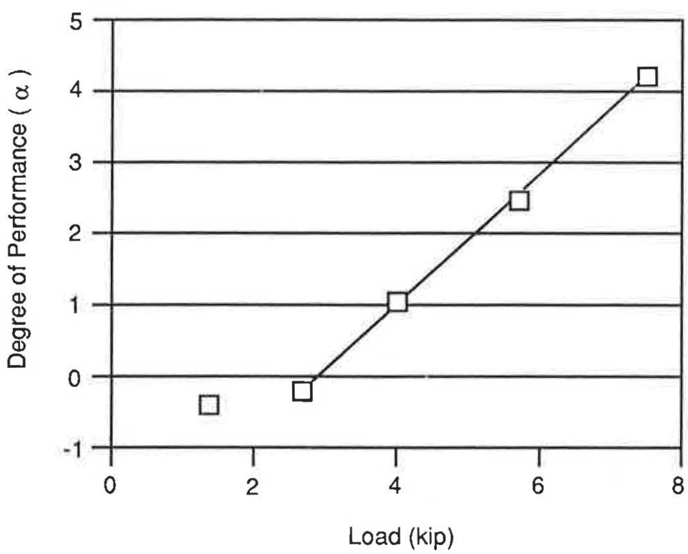

FIGURE 11 Degree of performance versus load with one-rib center load.

from composite strains, top of rib and valley of corrugation, resulted in much higher values than applied moments. Noncomposite calculations duplicated the theoretical values calculated from the applied load. Figure 10 shows that bending in the rib was not composite, because Gauge 54 (rib) records a higher strain than Gauge 5 (plate). If bending were composite, Gauge 5 would read slightly more positively. The results were similar to those for other loading configurations. To better understand the rib-plate response to load, the rib was removed and the ratio of plate stresses was recorded (Table 1). It should be noted that the ratio of stresses was constant, except where affected by supports. Because stresses can be calculated across the rib-plate interface, a composite thrust was added.

$$T = T_p + T_r + T_c$$

where

T_p = thrust in the plate,
T_r = thrust in the rib, and
T_c = the composite thrust calculated at 4 kips.

A plot of α (Figure 11) clearly shows that α becomes constant after the load reaches 3 kips.

Other configurations were also tested. When a two-rib plate was tested, a biaxial gauge was located beneath the rib. Measurements taken in this situation were composite for a concentrated center load (Figure 12) as well as a constant bending moment. In contrast to results by Beal (*3*), readings taken beneath the rib were more consistent with composite calculations. However, in Beal's study, the ribs were spaced 27 in. apart.

It is also interesting to note that in a laboratory situation, where fit is not a problem and torques can be exactly applied, the initial loading response was linear.

FIELD STRESS DISTRIBUTION AT BOLT CONNECTIONS

To investigate the stress distribution around bolts, three bolts were instrumented with patterns of electric strain rosettes. A live load 130 percent of the H20 loading applied to the center

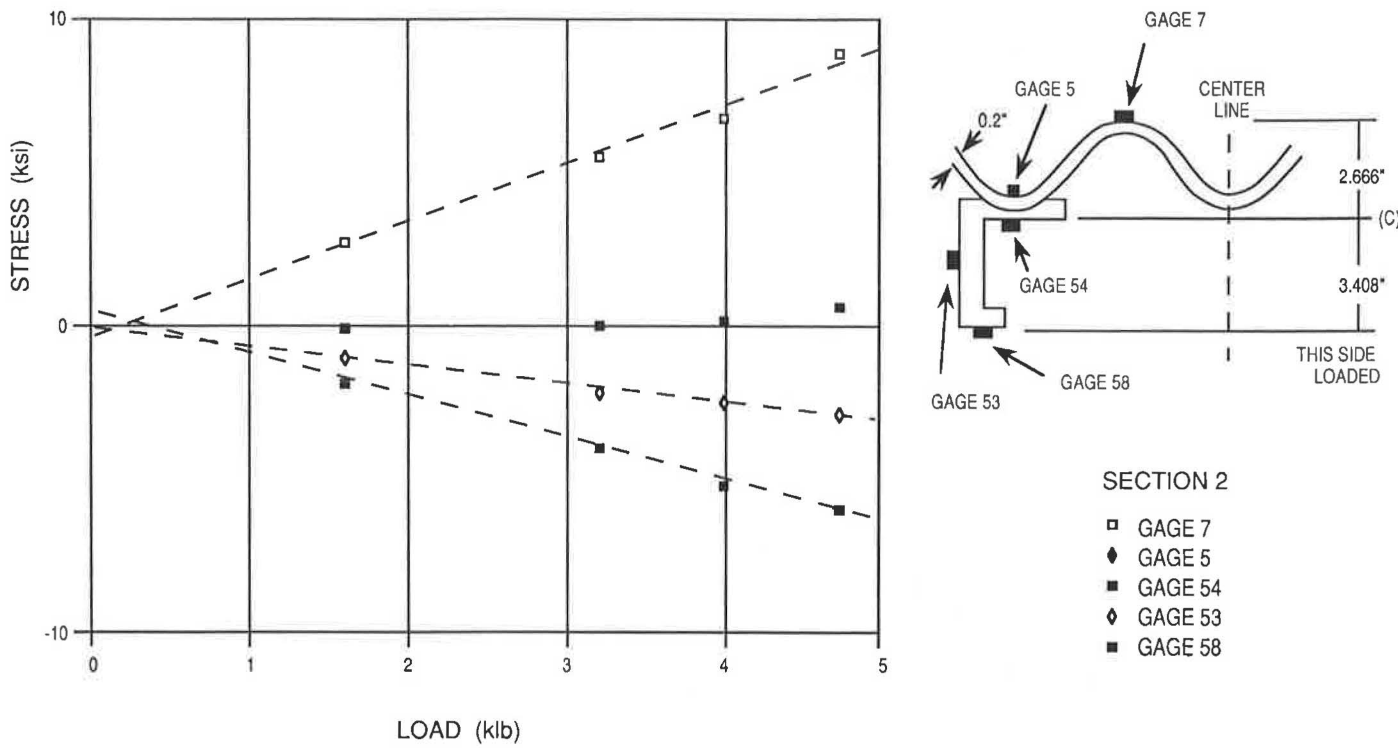

FIGURE 12 Laboratory test of center load, two-rib configuration.

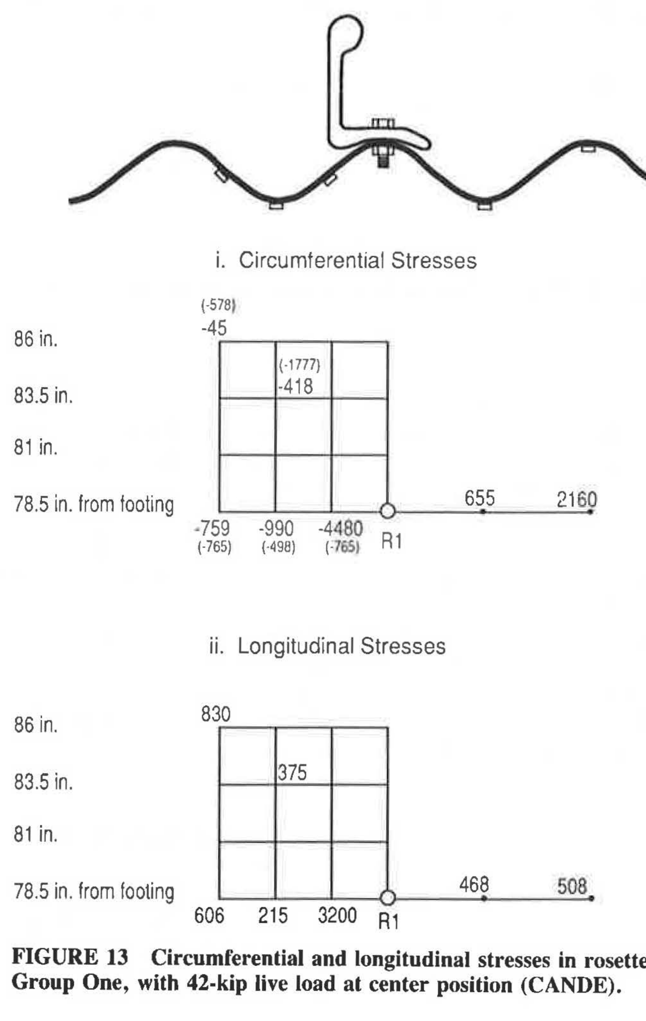

FIGURE 13 Circumferential and longitudinal stresses in rosette Group One, with 42-kip live load at center position (CANDE).

of the culvert resulted in circumferential and longitudinal stresses at the haunch as shown in Figure 13. The location of the instrumented bolt (R_1) is shown in Figure 4. To provide a comparison with values that may be determined theoretically, the culvert was modeled with the finite-element program CANDE. (The results of the computer program are given in parentheses in Figure 13.) For comparison, the culvert was assumed to act as a composite structure. When principal stresses were calculated, the stress concentration was more obvious, as shown in Figure 14. The reinforcing effect of the rib was clearly seen as the principal directions were rotated around the bolt. However, in general the comparison between CANDE and field measurements is good at the haunch.

At the end of the rib, located close to the footer (R_3 in Figure 4), there was no agreement between theory and field data. When compared with the finite-element solution from CANDE in Figure 15, the bolt clearly disrupted the stress distribution since the circumferential stresses decreased in magnitude away from the bolt. Large stresses close to the bolt represented stress concentrations and large local distortion. This occurred in circumferential as well as in the longitudinal directions. The plate, as it contacted the footer, also recorded stress disruptions. The crown corrugation on both sides of the bolt showed compressive stress yet did not agree in magnitude. A difference in magnitude suggests local distortion and a side force on the rib. Compressive stress, as calculated by CANDE, rather than the tensile stresses that were measured in the field, would be expected below the last bolt. The plot of principal stresses at the footer (Figure 16) again emphasizes the random stress field and high stress concentrations. On the basis of these measurements, it is suggested that the rib be extended into the footer.

Examining the effect of the bolted connection in the laboratory, a comparison was drawn between the plate only (no rib) and the plate with a central rib. Figure 17 shows that the stresses were linear with respect to distance along the corrugation, reaching almost zero at the hole (Position 4). The stresses continued to increase locally but returned to zero. The same rosettes with a rib bolted to the plate showed a compressive stress that increased as it passed the bolt location (Figure 18). In both cases, the stresses increased in proportion to load. The local effect of the connection, which was very apparent in the field measurements, could be clearly duplicated in the laboratory as shown in Figure 19. The values of stress within the parentheses were theoretical values calculated for a composite section. Compressive stresses appeared as a local stress effect created by the bolt.

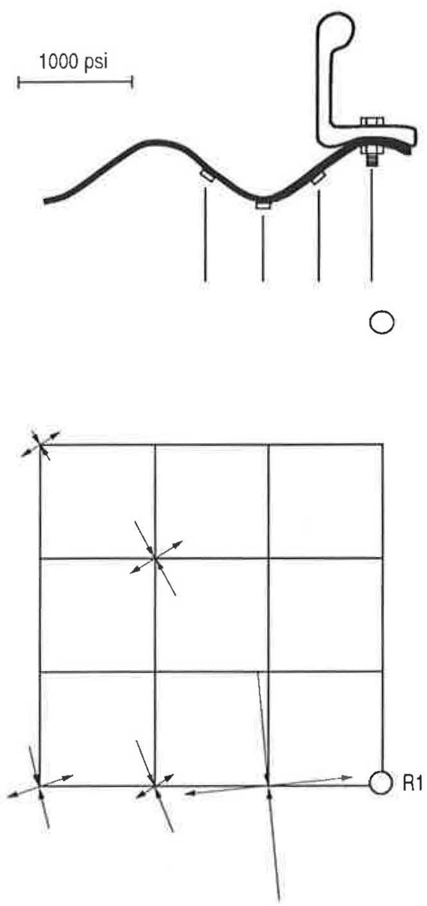

FIGURE 14 Principal stresses in rosette Group One, with 42-kip live load at center position.

CONCLUSIONS

The results for this field and laboratory investigation may be summarized as follows:

1. Many variables are involved in determining whether full composite action occurs in the rib-plate structure. The degree of composite action increases as backfill height increases and the culvert deformation returns from early peaking. Then composite response is recorded under live load. Slip may occur betweeen the plate and the stiffening ribs because the fit is not tight enough in the assembled culvert.
2. In the bolted connection, a linear response was recorded, yet the response does not represent the load response of the culvert. Local bending and stress concentration play a more decisive role in determination of the stress distribution around the bolt hole.
3. Because the end of the rib and the connection to the footer create a region of high local stresses, box-culvert design would be improved by extending the rib into the footer.
4. Because strains perpendicular to the corrugations are frequently larger than the circumferential strains, accurate stress determination depends on recording strains in both directions.
5. Field measurements are consistent with analysis by the finite-element computer program CANDE. However, CANDE cannot calculate local stress concentration around bolted connections.

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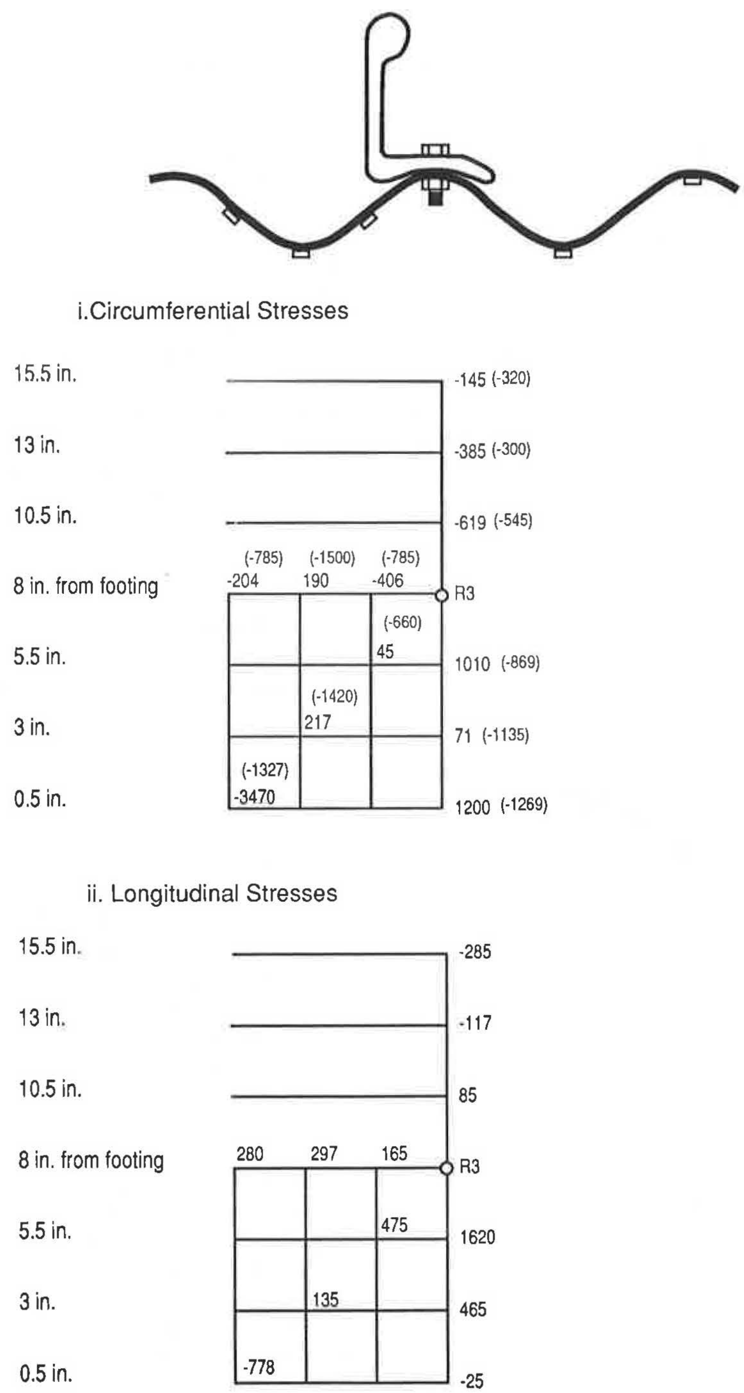


FIGURE 15 Circumferential and longitudinal stresses in rosette Group Three, with 42-kip live load at center position (CANDE).

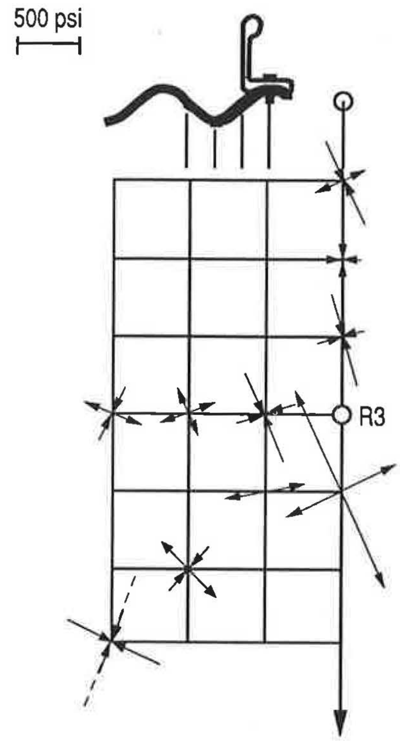


FIGURE 16 Principal stresses in rosette Group Three, with 42-kip live load at center position.

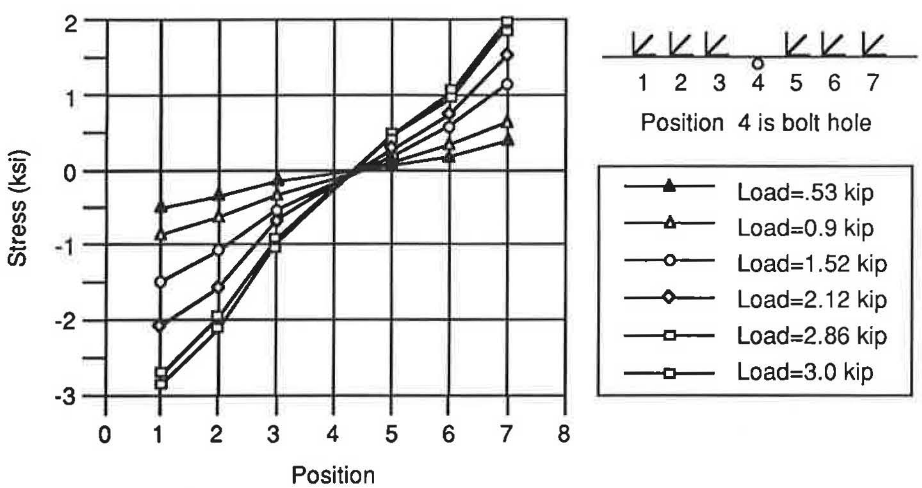


FIGURE 17 Rosette stresses lined up with bolt hole along corrugation direction for no-rib center load.

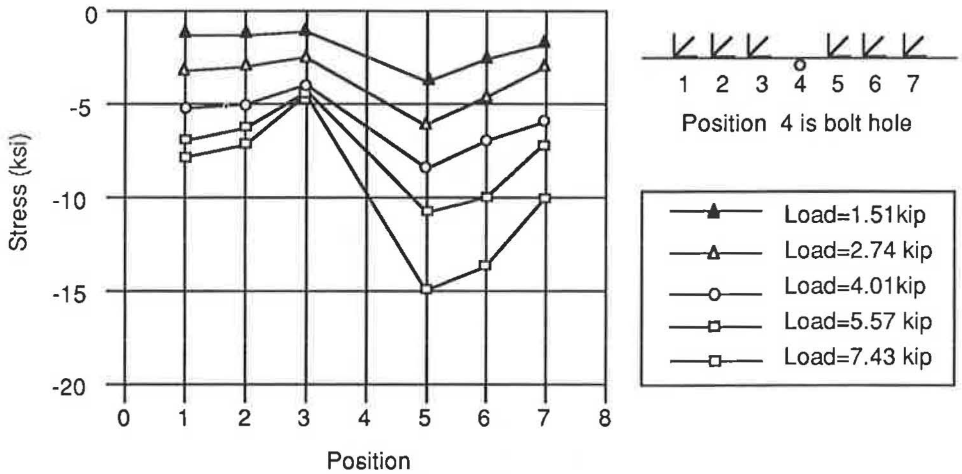
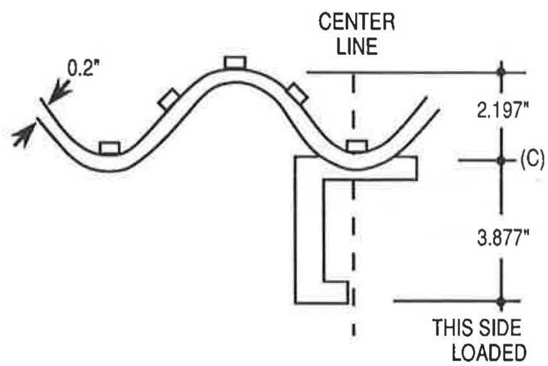


FIGURE 18 Rosette stresses lined up with bolt hole along corrugation direction for one-rib center load.



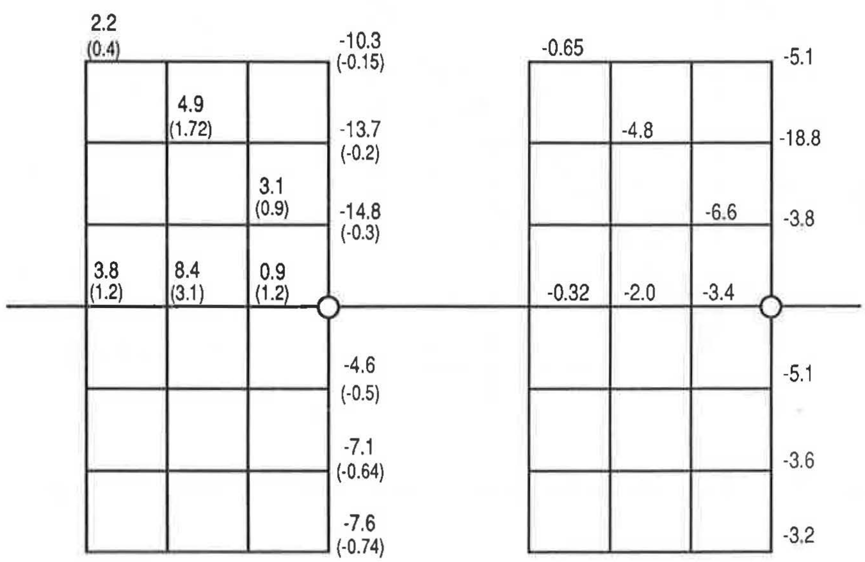


FIGURE 19 Circumferential and perpendicular stresses in rosette group located between Sections 3 and 4 with concentrated load, one rib, and at 7.43 kips.

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