Analysis of In-Service Jointless Bridges

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Jointless bridge systems are designed currently for primary loads only: for example, live load and dead load. The only secondary load that is considered while designing a jointless bridge is the temperature load. With respect to other secondary loads, such as creep and shrinkage of the superstructural material, it is assumed that the effects of creep and shrinkage are opposite in nature and cancel out each other. Designers have different opinions on earth pressure and settlement loads. To develop a proper explanation for jointless bridge behavior, a better insight into the performance of jointless bridges is needed in terms of primary as well as secondary loads. Five in-service jointless bridges were analyzed for primary and secondary loads by the state-of-the-art methods. The analytical data generated for one bridge are synthesized and presented. The discussion includes effect of primary and secondary loads, effect of secondary loads with respect to primary loads, and effect of different systems (boundary conditions) on stresses at various locations. The results reveal that the combination of integral stub abutment and a single row of piles makes the substructure flexible, thereby reducing the stresses at superstructure and abutment joint. The weak axis orientation of piles further reduces stresses at superstructure and abutment joint. The major contributor to total stresses is the temperature load. Creep of superstructural material is helpful in reducing the stresses at some locations. Shrinkage relieves creep to some extent but not completely. Earth pressure causes negligible stresses at all locations in the bridge. Settlement stresses are considerable in multispan jointless bridges.

Jointless bridge systems are designed currently for primary loads only, such as live loads and dead loads (*1,2*). The only secondary load that is considered while designing a jointless bridge is the temperature load. Typically, a single row of piles with an integral stub abutment is used to accommodate horizontal expansion or contraction as a result of temperature load. With respect to other secondary loads, such as creep and shrinkage of the superstructural material, it is assumed that the effects of creep and shrinkage are opposite in nature and cancel out each other. Designers have different opinions about earth pressure and settlement loads. However, there is no literature available that addresses the effect of primary and secondary loads in terms of magnitude of stresses and deformations induced in jointless bridges. Although jointless bridges operate under very high secondary stresses, they are found to function extremely well, and the distress has been nominal (*3*). To develop an appropriate explanation for jointless bridge behavior that would fit field data, a better insight into the performance of jointless bridges is needed under temperature, creep, shrinkage, settlement, and other forces.

OBJECTIVES

The objectives of this paper are to (*a*) identify the state-of-the-art methods of analysis for in-service jointless bridges; (*b*) prioritize loads for analysis of in-service jointless bridges; (*c*) present synthesized analytical data that aid in understanding the behavior of jointless bridges; and (*d*) study the effects of primary and secondary loads, boundary conditions, and system flexibility on the stresses at various locations in the jointless bridge system.

SCOPE

Five in-service jointless bridges (Table 1) were analyzed by state-of-the-art methods of analysis. Because of space limitations, the results for only one bridge (Lone Tree Road Bridge, Iowa) are presented here (Tables 2 through 5). The structural details were extracted from the drawings supplied by various state highway departments. The loads considered in the analysis were (*a*) dead load or self-weight (DL); (*b*) dead load plus creep of the superstructural material (DL + C); (*c*) live load (LL); (*d*) temperature gradient across the depth of the superstructure (TG); (*e*) uniform temperature across the depth of the superstructure; (*f*) uniform shrinkage of the superstructural material (SH); (*g*) differential settlement (SE); and (*h*) earth pressure (EP). These loads are schematically represented in Figure 1. After a thorough study, it was found that uniform temperature was unrealistic because it rarely exists in practice; because of this, uniform temperature load was omitted in later analyses. For each bridge and for each load case, several boundary conditions were considered. The boundary conditions were considered in such a manner that minimum to maximum system flexibility was achieved. The bridge superstructures considered for analysis were made of concrete deck stiffened with steel stringers. The abutments were of stub type. Four bridges were symmetrical and one bridge was unsymmetrical. Four bridges were skewed and one bridge was straight. The maximum skew occurred for a single-span bridge, and it was 20 degrees 29 minutes. In the analyses, the skew was ignored. More details about these five bridges appear elsewhere (*4*). Furthermore, the results in terms of internal forces and corresponding stresses were tabulated and evaluated.

ANALYSIS METHOD

In the past, two-dimensional frame models (*5*) included the flexural stiffness of piles, the axial and flexural stiffnesses of the deck and girders, and the axial and flexural stiffnesses of the integral abutment. Girton et. al. (*b*) reported that excellent correlation was obtained between the results predicted by the two-dimensional (2-D) frame models and the values measured in the field. The 2-D frame models are simpler in the sense that they use ordinary beam elements, and the preparation of the model is faster than for three-dimensional (3-D) models requiring higher-order elements. Another advantage of 2-D models is their suitability for parametric study. In this paper, the jointless bridges are idealized and analyzed as 2-D frame models. The age-adjusted effective modulus method was used for creep and shrinkage analysis. Thermal stress

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TABLE 1. Details of In-Service Jointless Bridges Analyzed (1 ft = 0.3 m; 1 in. = 2.5 cm; 1 psi = 6.89 kPa)

Serial No.	Name of the Bridge	Location of the Bridge	Bridge Details
1	Short Creek Road Bridge	Brooke and Ohio ounty, West Virginia	Span: Single span of 110 ft.; Width: 40 ft.; No. of stringers and spacing: 6 with 106 in.; Skew angle: 20°-29'; Abutment height: 98 in.; Piles: Single row of HP 12x53; Pile orientation: Strong axis bending; Design live load: HS 25-44; Concrete strength: 3.122 million psi for superstructure and 3.605 million psi for substructure.
2	Lone Tree Road Bridge	Black Hawk County, Iowa	Span: Two-span of 114ft.-114 ft.; Width: 40 ft.; No. of stringers and spacing: 5 with 111 in.; Skew angle: 8°; Abutment height: 96 in.; Piles: Single row of HP 10x42; Pile orientation: Weak axis bending; Design live load: HS 20-44; Concrete strength: 3.37 million psi for superstructure and substructure.
3	South Saturn Parkway	Maury County, Tennessee	Span: Two-span of 132.5 ft.-117.5 ft.; Width: 40 ft.; No. of stringers and spacing: 6 with 120 in.; Skew angle: 18°; Abutment height: 88 in.; Piles: Single row of HP 10x42; Pile orientation: Weak axis bending; Design live load: HS 20-44; Concrete strength: 3.12 million psi for superstructure and substructure.
4	Over Creek Road Bridge	Jones County, South Dakota	Span: Three-span of 68 ft.-87 ft.-68 ft.; Width: 46 ft.; No. of stringers and spacing: 5 with 102 in.; Skew angle: 0°; Abutment height: 73.5 in.; Piles: Single row of HP 10x42; Pile orientation: Weak axis bending; Design live load: HS 20-44; Concrete strength: 3.6 million psi for superstructure and substructure.
5	Bridge Over Little Kanawha River	Upshur County, West Virginia	Span: Three-span of 45 ft.-60 ft.-45 ft.; Width: 22 ft.; No. of stringers and spacing: 4 with 96 in.; Skew angle: 20°; Abutment height: 77.2 in.; Piles: Single row of HP 10x42; Pile orientation: Weak axis bending; Design live load: HS 25-44; Concrete strength: 3.8 million psi for superstructure and 3.12 million psi for substructure.

Note: The superstructure of all bridges is made of concrete slab composite with steel stringers.

TABLE 2. Stresses at Superstructure and Abutment Joint in Various Systems (1 ksi = 6890 kPa)

Load Case	Stresses (ksi)					Remarks
	System A	System B	System C	System D	System E	
DL	0.382 -13.16	0.353 -13.15	0.353 -13.15	0.0033 -0.094	0.00113 -0.0323	The dead load stresses in Systems D and E are negligible because of the flexibility of the substructure. These Systems behave like simply supported structures.
DL+C	0.272 -14.67	0.219 -14.61	0.219 -14.61	0.00304 -0.145	0.00104 -0.0497	The effect of creep is to decrease the top tensile stresses and to increase bottom compressive stresses. Creep effect is smaller in flexible Systems D and E when compared to stiffer Systems A through C.
LL	0.301 -10.65	0.286 -10.65	0.239 -8.4	0.00236 -0.0674	0.00081 -0.0231	The live load stresses in Systems D and E are negligible because of the flexibility of the substructure. These Systems behave like simply supported structures.
TG	0.123 -8.29	0.934 -8.58	0.914 -8.58	0.480 7.56	0.479 7.58	The top tensile stresses due to temperature gradient are lower in Systems D and E. The bottom stresses in Systems D and E which are tensile in nature are within allowable stress values for steel.
SH	0.239 1.04	0.0791 1.23	0.0791 1.23	0.0765 1.38	0.0759 1.41	Stresses due to shrinkage are negligible in Systems D and E.
SE	0.136 -4.37	0.117 -4.36	0.117 -4.36	0.00119 -0.034	0.00119 -0.0342	Settlement causes negligible stresses in Systems D and E.
EP	0.0006 -0.0027	0.0024 -0.0074	0.0052 -0.1121	0.057 -1.43	0.0567 -1.43	Earth pressure causes negligible stresses in all Systems.
TOTAL	1.07 -36.93	1.62 -36.97	1.57 -34.82	0.62 7.31	0.62 7.46	The total stresses are lower in Systems D and E compared to other Systems. During winter these stresses are further reduced due to opposite nature of stresses caused by temperature gradient.

Note: Positive stresses indicate tensile stresses.
Total is the sum of DL+C, LL, TG, SH, SE and EP.

TABLE 3. Stresses at Midspan of First Span in Various Systems (1 ksi = 6890 kPa)

Load Case	Stresses (ksi)					Remarks
	System A	System B	System C	System D	System E	
DL	-0.335 6.42	-0.357 6.22	-0.357 6.22	-0.342 9.34	-0.343 9.35	Top compressive stresses are nearly same in all Systems and bottom tensile stresses are higher in Systems D and E. Though, Systems D and E behave like simply supported structures, the intermediate support moment effect the midspan stresses.
DL+C	-0.188 6.93	-0.221 6.11	-0.221 6.11	-0.218 10.24	-0.219 10.26	The effect of creep is to decrease top compressive stresses and to increase bottom tensile stresses.
LL	-0.365 7.52	-0.376 7.43	-0.399 8.51	-0.390 10.65	-0.390 10.65	Top compressive stresses are nearly same in all Systems and bottom tensile stresses are higher in Systems D and E. Though Systems D and E behave like simply supported structures, the intermediate support moment effect the midspan stresses.
TG	-0.278 2.59	0.309 7.91	0.309 7.91	0.318 12.00	0.317 12.01	The top tensile stresses due to temperature gradient are almost same in Systems B through E and the bottom stresses due to temperature gradient are higher in Systems D and E compared to other Systems.
SH	0.281 -0.714	0.181 -2.99	0.181 -2.99	0.181 -2.92	0.180 -2.91	Stresses due to shrinkage are almost same in Systems B through E.
SE	-0.0394 0.513	-0.0559 0.362	-0.0559 0.362	-0.054 1.46	-0.054 1.46	Settlement causes negligible stresses in all Systems.
EP	0.00037 0.00373	0.0015 0.017	0.0028 -0.04833	0.033 -0.785	0.033 -0.786	Earth pressure causes negligible stresses in all Systems.
TOTAL	-0.586 16.85	-0.161 18.83	-0.182 19.85	-0.131 30.64	-0.132 30.68	The total bottom stresses are higher in Systems D and E, and exceed allowable limits of steel. However, these stresses are reduced during winter due to opposite nature of temperature stresses.

Note: Positive stresses indicate tensile stresses.
Total is the sum of DL+C, LL, TG, SH, SE and EP.

TABLE 4. Stresses at Pier in Various Systems (1 ksi = 6890 kPa)

Load Case	Stresses (ksi)					Remarks
	System A	System B	System C	System D	System E	
DL	0.462 -11.2	0.447 -11.39	0.447 -11.39	0.753 -15.41	0.754 -15.43	The top tensile and bottom compressive stresses are higher in Systems D and E.
DL+C	0.269 -12.26	0.256 -13.14	0.256 -13.14	0.401 -16.72	0.402 -16.75	The effect of creep is to decrease top tensile stresses and to increase bottom compressive stresses.
LL	0.325 -7.51	0.315 -7.67	0.311 -7.89	0.517 -10.58	0.518 -10.59	The top tensile and bottom compressive stresses are higher in Systems D and E.
TG	0.044 9.68	0.452 14.49	0.452 14.95	0.812 10.24	0.813 10.24	The top tensile stresses are higher and bottom tensile stresses are lower in Systems D and E.
SH	0.329 -1.58	0.287 -4.01	0.287 -4.01	0.288 -4.02	0.289 -4.02	Shrinkage stresses are almost same in Systems B through E.
SE	-0.168 3.08	-0.179 2.93	-0.178 2.93	-0.082 1.68	-0.082 1.67	Settlement cause negligible stresses in System D and E.
EP	-0.00007 -0.0011	0.00031 -0.0055	0.00055 0.0075	0.0078 -0.084	0.0078 -0.084	Earth pressure causes negligible stresses in all Systems.
TOTAL	0.799 -8.59	1.13 -6.93	1.13 -7.14	1.94 -19.48	1.94 -19.53	The total stresses are higher in Systems D and E. The pier section of jointless bridges have to be carefully designed for higher top tensile stresses.

Note: Positive stresses indicate tensile stresses.
Total is the sum of DL+C, LL, TG, SH, SE and EP.

TABLE 5. Stresses at Abutment Bottom in Various Systems (1 ksi = 6890 kPa)

Load Case	Stresses (ksi)					Remarks
	System A	System B	System C	System D	System E	
DL	-0.127 0.0937	-0.0164 -0.0164	-0.0164 -0.0164	-0.0155 -0.0963	-0.0135 -0.115	The stresses due to dead load are negligible in all Systems.
DL+C	-0.289 0.256	-0.0162 -0.0162	-0.0162 -0.0162	-0.0167 -0.0084	-0.0139 -0.011	The effect of creep is significant in System A because of fixity. The final stresses (DL+C) are negligible in all other Systems.
LL	-0.067 0.0457	-0.0109 -0.0109	-0.0107 -0.0107	-0.0102 -0.0059	-0.0089 -0.0073	The stresses due to live load are negligible in all Systems.
TG	3.03 3.04	-0.0064 -0.0064	-0.0064 -0.0064	-0.0026 -0.000825	-0.00203 -0.0014	The stresses due to temperature gradient are significant in System A because of fixity. In all other Systems, the stresses are negligible.
SH	-0.787 0.787	0.0015 0.0015	0.0015 0.0015	0.00042 0.00267	0.0017 0.0019	The stresses due to shrinkage are significant in System A because of fixity. In all other Systems, the stresses are negligible.
SE	-0.0877 -0.0839	-0.0018 -0.0018	-0.0018 -0.0018	-0.00165 0.00049	-0.0017 0.00049	Settlement induce negligible stresses in all Systems.
EP	0.0063 -0.0063	-0.000009 -0.000009	-0.000024 -0.000024	-0.0627 0.0622	-0.0627 0.0622	Earth Pressure Induce negligible stresses in all Systems.
TOTAL	4.04 1.80	-0.092 -0.092	-0.034 -0.034	0.050 -0.093	0.045 -0.088	The total stresses are higher in System A because of fixity. Therefore, this System should be avoided for jointless bridges.

Note: Positive stresses indicate tensile stresses.
Total is the sum of DL+C, LL, TG, SH, SE and EP.

analysis was based on one-dimensional beam theory. More details on the methods of analysis can be found elsewhere (*4*).

DIFFERENT SYSTEMS FOR ANALYSIS

Lone Tree Road Bridge (Table 1) is analyzed as Systems A through E. The systems are schematically represented in Figure 2. Systems A through C idealize the bridge with spread footing type of foundation, whereas Systems D and E idealize the bridge with pile type of foundation. The maximum system stiffness is for System A, and the minimum system stiffness is for System E. In other words, System A has minimum flexibility or larger restraint to movement, and System E has maximum flexibility or least restraint to movement. For discussion purposes, jointless bridges on spread footing are regarded as stiffer systems, and jointless bridges on pile foundation are regarded as flexible systems.

RESULTS

The internal forces and moments were determined for various load cases and at various locations, such as superstructure and abutment joint, midspan, superstructure at pier, and foundation level. The top and bottom stresses computed at the above locations included the effect of bending moment and axial force. Because of the length limitation of this paper, tables showing stresses for only one bridge (Lone Tree Road Bridge, Iowa) are presented here. More details about the results of other bridges are available elsewhere (*4*). A qualitative summary is presented in the following sections, and it includes the effect of primary and secondary loads, the effect of secondary loads compared with primary loads, and the effect of various systems (boundary conditions) on stresses at these locations.

STRESSES AT SUPERSTRUCTURE AND ABUTMENT JOINT

Dead Load

Dead load produces considerable top tensile stresses in Systems A through C. These systems are founded on spread footings. The highest tensile stress (382 psi; Table 2) is for System A. With those bridges resting on piles, top tensile stresses caused by dead load are found to decrease drastically. The decrease in tensile stresses caused by dead load is about 300 times that of when the foundation type is changed from spread footing to piles (System A through System E). For the same bridge, weak axis bending of piles results in 3 times lower stresses than strong axis bending of piles. The bottom compressive stresses in steel stringer are higher in bridges without piles, and the maximum value is about 13 ksi. The bottom stresses are low in bridges resting on piles. Weak axis orientation of piles further reduces the bottom stresses. On the basis of the above discussion, it is preferable to have jointless bridges on piles that bend about their weak axis.

Creep

Change in the internal forces as a result of creep is advantageous with regard to the top tensile stresses at the superstructure and abutment joint. The advantage lies in the fact that the top tensile stresses caused by dead load at the superstructure and abutment joint are decreased. The advantage caused by creep is maximum in stiffer systems and minimum in flexible systems. The maximum decrease in top tensile stresses at the superstructure and abutment joint is about 40 percent (bridges on spread footing), and the minimum decrease is about 10 percent (bridges on pile foundation).

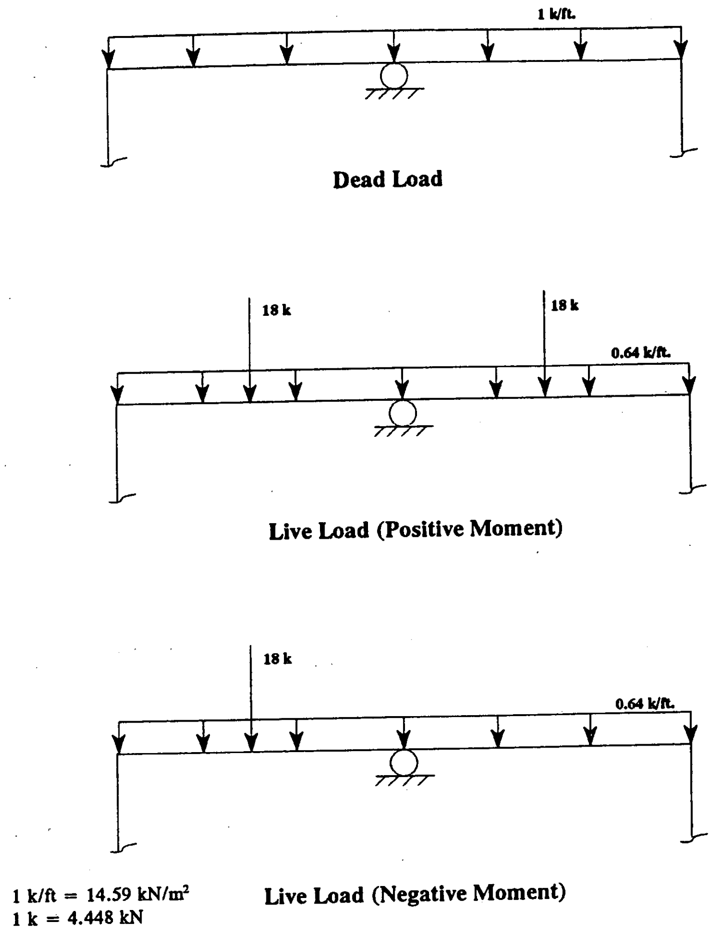

FIGURE 1. Loads considered for analysis ***(continued on next page).***

Creep increases bottom compressive stresses in steel. However, the final stresses in bottom steel after an increase caused by creep are well within the allowable stresses for steel.

Live Load

Live load stresses at the superstructure and abutment joint are nearly 40 percent of dead stresses. The trend of live load stresses is the same as that of dead load. Therefore, the discussion presented above for dead load holds good for live load also. In conclusion, as far as dead and live loads are concerned, jointless bridges should be supported on piles that bend about their weak axes. This helps in reducing tensile stresses at the top of the superstructure and abutment joint.

Temperature Gradient

Stresses produced by temperature gradient at the superstructure and abutment joint are tensile in nature at top and tensile (flexible systems) or compressive (stiffer systems) in nature at the bottom. The maximum top tensile stress is found to be about 900 psi in the case of stiffer Systems B and C. These stresses are reduced to nearly half in the case of a jointless bridge with pile foundation. Furthermore, the maximum bottom tensile and compressive stresses are found to be, respectively, 7.5 ksi (Systems D and E) and 8.5 ksi (Systems A through C). The temperature gradient is detrimental to the bridge in terms of producing considerable top tensile stresses at the superstructure and abutment joint.

Shrinkage

In a superstructural system composed of concrete slab and steel girder, there is nonuniform shrinkage through the depth, in the sense that concrete shrinks and steel does not, and this effect complicates the analysis. Shrinkage produces top tensile stress in the superstructure and abutment joint of all systems. Shrinkage produces considerable top tensile stresses in stiffer System A and negligible stresses in flexible Systems D and E.

Settlement

Settlement stresses are considerable in bridges resting on spread footing. The stresses are negligibly small in bridges resting on piles (Systems D and E). The effect of settlement is the same as that of primary loads in all the systems. The stresses are nearly one-fourth of dead load stresses in stiffer systems (Systems A through C). Therefore, a pile foundation is preferable to avoid the development

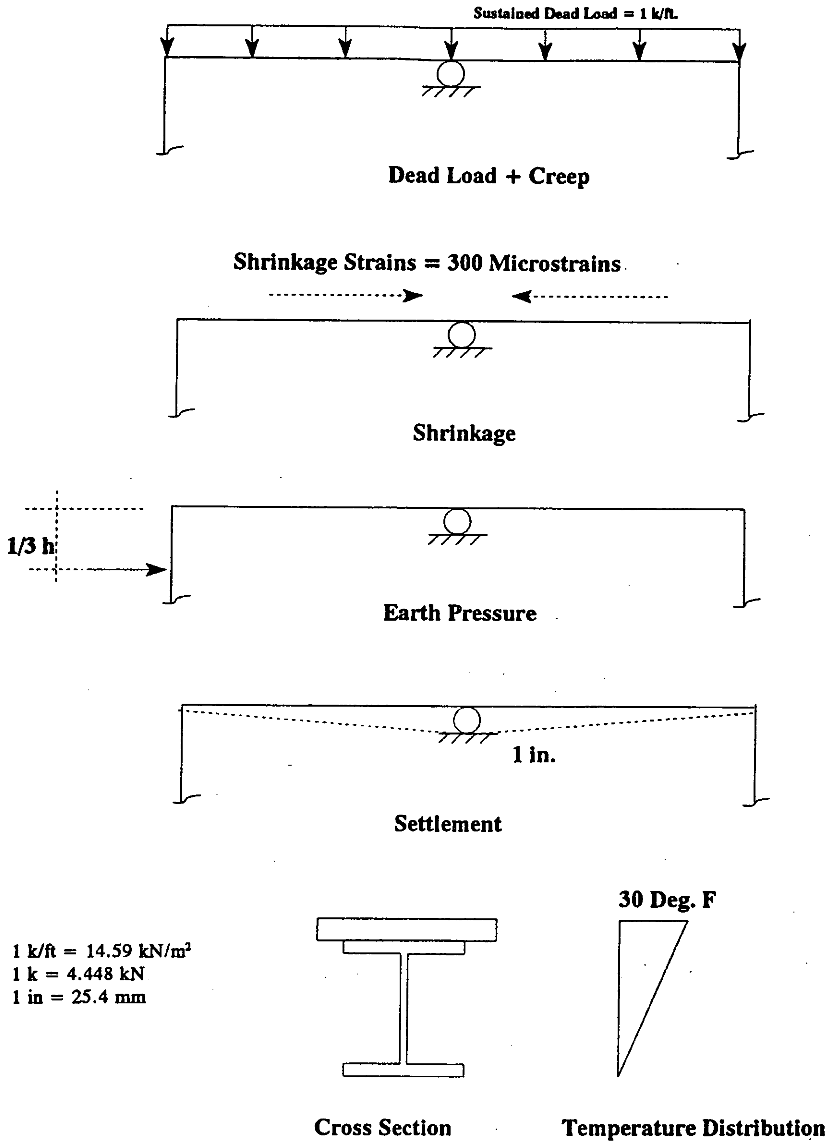

FIGURE 1 (*continued*).

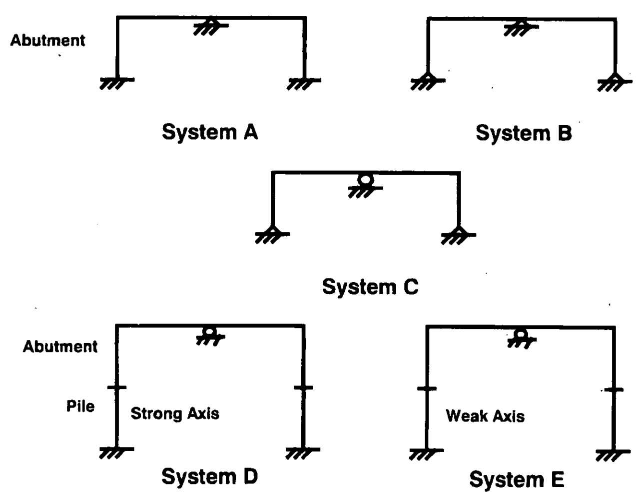

FIGURE 2. Analysis of Lone Tree Bridge (Iowa) Systems A through E.

of large stresses at the superstructure and abutment joint as a result of settlement.

Earth Pressure

Earth pressure (active case) acts on one leg in the form of a point load and produces negligible stresses at all locations in all systems. The stresses are not going to be significant even if the active case is converted (three to four times greater) to the passive case. Therefore, the effect of earth pressure is insignificant and is not presented in future sections. Also, while designing a jointless bridge the effect of earth pressure can be ignored.

Total Stresses

Top total stresses in bridges resting on pile foundation are 2.5 times lower than the same stress in bridges resting on spread footing. The maximum top and bottom stresses in bridges resting on pile foundations are found to be around 600 psi and 7.5 ksi, as against 1,600 psi and 36 ksi in stiffer systems, respectively. The major contributor to total stresses in flexible systems is the temperature gradient. A reverse temperature gradient in winter causes opposite stresses, which may be helpful in reducing the total stresses.

STRESSES AT MIDSPAN

Dead load

Dead load produces compressive stresses at top and tensile stresses at the bottom of the midspan section. The top compressive stresses at the midspan of the bridge with pile foundations are nearly the same as the stresses at the midspan of the bridge with spread footings. The bottom steel stresses are higher in flexible systems than in stiffer systems (Table 3). The maximum top compressive stress for concrete and bottom tensile stress for steel are found to be around 350 psi and 10 ksi in flexible systems and around 350 psi and 6 ksi in stiffer systems.

Creep

Top compressive stress caused by dead load at midspan section decreases as a result of creep. The maximum decrease in compressive stress is found to be nearly 40 percent. The dead load bottom tensile stresses increase because of creep. The maximum increase is less than 10 percent.

Live Load

Live load produces compressive stresses at top and tensile stresses at the bottom of the midspan section. The top and bottom live load stresses are nearly the same as those of the dead load stresses.

Temperature Gradient

Temperature gradient produces tensile stresses at the top and bottom of the midspan section for most of the systems. The tensile stresses produced by the temperature gradient are opposite those produced by gravity loads. Thus, temperature stresses nullify to some extent the compressive stresses produced by the gravity loads. The highest top tensile stress is found to be around 320 psi (Systems D and E), and the highest bottom tensile stress is found to be 12 ksi (Systems D and E).

Shrinkage

Shrinkage produces tension at the top and compression at the bottom of the midspan section in all the systems. The stresses caused by shrinkage are opposite those produced as a result of dead and live load. As a result, stresses caused by gravity loads are nullified to some extent. This is an added advantage in jointless bridges.

Settlement

The top and bottom stresses vary from 10 to 20 percent of the top and bottom dead load stresses in the midspan.

Combined stresses

The sum of stresses caused by all loads indicates that the midspan section of flexible systems is subjected to a smaller compressive stress at the top and larger tensile stress at the bottom when compared with stiffer systems. The bottom tensile stress in flexible systems is so high that it exceeds the allowable stress value in steel. A reverse gradient in winter would induce an opposite nature of stresses. This would decrease the bottom tensile stresses. The maximum compressive and tensile stresses developed at the top and bottom are nearly 200 psi and 30 ksi, respectively.

STRESSES IN SUPERSTRUCTURE AT PIER

Dead Load

The negative moment induced at the pier causes top tensile stresses and bottom compressive stresses. Most flexible systems have a disadvantage too: they produce larger top and bottom stresses at the pier than those produced in stiffer systems. The increase in tensile stresses in flexible systems can be nearly twice those found in stiffer systems (Table 4). To counteract the high tensile stresses the following may be necessary: additional reinforcement to confine concrete over the pier; an increase in the deck thickness by means of a haunch over the pier, or prestressing the slab over the pier.

Creep

The top tensile stresses caused by creep in all bridge systems decrease by about 50 percent. The bottom compressive stresses caused by creep increase by a maximum of 10 percent. As stated earlier, superstructure section over the pier of the most flexible systems is subjected to larger tensile stresses. These large tensile stresses are reduced to nearly half as a result of creep, thereby nullifying the tensile stresses to some extent.

Live Load

Live load stresses at the top of the deck over the pier are about 25 percent greater than the top dead load stresses. However, bottom stresses are nearly 40 percent lower than dead load bottom stresses.

Temperature Gradient

A temperature gradient produces tensile stresses at the top and bottom of all systems, which is somewhat detrimental to a jointless bridge system because it adds to the tensile stresses caused by other loads and increases the potential of cracking. The tensile stresses can be as high as 800 psi in concrete and 15 ksi in steel, as indicated in Table 4.

Shrinkage

Over a pier, shrinkage produces tensile stresses at the top and compressive stresses at the bottom in all the systems. This creates the worst scenario because the primary loads also produce tensile stresses at the top fiber and compressive stresses at the bottom. The top concrete may not be able to resist these tensile stresses and may crack. The crack thus formed may simulate over an artificial hinge at the pier. Because the abutment and superstructure joint acts like hinge because of large flexibility, the spans may behave as simply supported. The question then is whether jointless bridges should be designed as simply supported bridges. As discussed in earlier sections, there is a decrease in tensile stresses caused by creep, whereas an inducement of tensile stresses is noted because of shrinkage. Therefore, shrinkage stresses cancel out each other to some extent. In other words, "creep relieves shrinkage." Therefore, the common design assumption that creep and shrinkage have opposite effects is a reasonable one.

Settlement

The top and bottom stresses developed over a pier as a result of settlement is opposite in nature to those stresses developed under dead loads and live loads. This causes a relief in stress by reducing the large tensile stresses caused by other loads at the pier. Because of settlement, the maximum top and bottom stresses are found to be nearly 25 percent of dead load stresses. Therefore, stress reduction of a maximum of 25 percent in dead load stresses over a pier is reasonable.

Combined Stresses

The total stresses over a pier are higher in flexible systems than in stiffer systems. The maximum tensile stress at a top fiber is found to be 2,000 psi, and the maximum compressive stress at bottom fiber is found to be 20 ksi.

STRESSES AT FOUNDATION LEVEL

Dead Load and Live Load

With reference to stresses at the foundation level (footing level for bridges on spread footing-type foundations and abutment-pile junction level for bridges resting on pile-type foundations), System A necessitates the design of footing for large stresses induced because of fixity. The placement of a hinge at the footing level causes the stresses to decrease greatly. Therefore, it is better to have a hinge between the abutment and footing to reduce stresses if a jointless bridge is built with spread footings. In the case of jointless bridges that rest on piles, the stresses in concrete at the point where piles are fixed to the abutment are very small. Thus, there is no fear of concrete cracking or separation of abutment from piles.

Creep

The rigid spread footing (System A) is subjected to greater stresses compared with flexible spread footing (System B) because of the moment that develops as a result of support rigidity. A large increase in creep stresses is noted in the case of fixed footing, as all the internal forces are transferred to footing. An increase of nearly 125 to 150 percent is found at the footing level in the case of System A. Therefore, creep behavior is favorable for Systems B through E where hinged spread footings or piles are attached to an abutment.

Temperature Gradient

When compared with other bridge systems, the foundation stresses are the highest for System A. This is because of the fixity of the foundation, which develops large moment and axial force. All other systems are subjected to negligible stresses at the foundation level.

Shrinkage

Shrinkage stresses are negligible at the foundation level in all systems except in the case of a fixed foundation. The restraint produced by fixity induces large stresses caused by shrinkage. The stresses at the joint between the abutment and piles are negligible, and there is no danger of cracking or separation.

Settlement

Settlement stresses developed at the foundation level are very small in all systems except for System A. The fixity at the foundation level in System A is the reason for the inducement of high stresses. For sites where settlement of soil strata is anticipated, it is better to have jointless bridges on piles, and the piles should be driven to reach hard strata.

Combined Stresses

The stresses are higher in System A than in any other bridge system, which is attributed to fixed boundary conditions. In all other systems, the total stresses are negligible. Therefore, System A should be avoided in the design of jointless bridges. The lower stresses at the junction of the pile and the abutment indicate that the junction is safe against cracking or separation.

CONCLUSIONS

From the synthesized analytical data, the following conclusions can be drawn:

1. Combination of integral stub abutment and single row of piles to bend about their weak axis, makes the substructure flexible, and the jointless bridge behaves like a simply supported structure, with reduced stresses.

2. The major contributor to the total stresses is the temperature load.

3. Creep of concrete is helpful in reducing the bending-induced stresses.

4. Shrinkage relieves creep to some extent but not completely.

5. Earth pressure causes negligible stresses at all locations in the bridge.

6. Settlement stresses are considerable in multispan jointless bridges.

7. The total stresses at the superstructure and abutment (resting on pile foundations) joint are lower than the stresses in bridges resting on spread footings. The major contributor to total stresses is the temperature gradient. A reverse temperature gradient in winter causes opposite stresses, which may be helpful in reducing total stresses.

8. When the total stresses are taken into account, the midspan section is subjected to smaller compressive stresses at the top and larger tensile stress at the bottom. The total bottom tensile stress is so high that it exceeds the allowable stress value in steel. A reverse gradient in winter would induce an opposite nature of stresses, which would decrease the high bottom tensile stresses.

9. The top of the concrete deck over the pier is subjected to high tensile stresses. Additional reinforcement to confine concrete over the pier, increase the deck thickness by means of a haunch over the pier, or even prestress the slab over the pier may have to be adopted to counteract the high tensile stresses.

10. At the foundation level, total stresses are higher in System A than in any other bridge system, which is attributed to a fixed boundary condition. In all other systems, the total stresses are negligible. Therefore, System A should be avoided in the design of jointless bridges. The lower stresses at the pile and the abutment joint indicate that the joint is safe against cracking or separation.

ACKNOWLEDGMENTS

The research project was sponsored by the West Virginia Department of Highways and United States Department of Transportation, FHWA. Their financial support is gratefully acknowledged.

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Publication of this paper sponsored by Committee on General Structures.