Observations from Shore Load Measurements during Concrete Construction

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Abstract: Loads during construction are highly variable and are often far in excess of what might be considered reasonable for purposes of design. While formwork design is still generally the responsibility of the contractor, increased attention is being paid to the engineered design of these and other temporary support systems. The relative frequency of failures of structures during construction versus those during service suggest that an engineered approach to formwork design in certain construction situations may be warranted. In this paper, initial observations from actual shore load measurements are made and the implications for design and construction are discussed. Specific attention is paid to the shore load effect (i.e., that value of load to which the shoring element is actually subjected). The work reported in this paper is part of an ongoing project to develop recommendations for design during construction. The qualitative analysis described herein provides much needed information on the magnitude and variations in load effect. In addition, this information can be used to relate the applied loading (i.e., actual loads on the slab) to the shore load effect, thereby providing information on load-structure interaction that may be important for safe design and construction of formwork systems.

INTRODUCTION

Loads during construction are highly variable and are often far in excess of what might be considered reasonable for purposes of design. While formwork design is still generally the responsibility of the contractor, increased attention has been paid to the engineered design of these and other temporary support systems. The relative frequency of failures of structures during construction versus those during service suggest that an engineered approach to formwork design in certain construction situations may be warranted. Recent studies have examined loads during reinforced concrete construction through extensive inventory and survey data collection (Ayoub and Karshenas 1994; Karshenas and Ayoub 1994). The objective of this work was to develop equivalent uniform loads for design purposes based on a statistical analysis of the survey data collected from various project sites. The approach was similar to that used for modeling occupancy live loads (Chalk and Corotis 1980). Other recent studies have examined load distribution associated with concrete placement patterns, both experimentally (Rosowsky et al. 1994a) and analytically (Peng et al. 1996). Finally, a limited amount of actual shore load data was collected (Fattal 1983). To date, no synthesis of the aforementioned research has been attempted.

In this paper, observations from actual shore load measurements will be described, along with the implications for design and construction. Specific attention is paid to the shore load effect (i.e., that value of load to which the shoring element is actually subjected). The work reported in this paper is part of an ongoing project to develop recommendations for design during construction. Anticipated outcomes from this project, funded by the National Institute of Occupational Safety and Health, include recommendations for design loads and factors to account for effects such as impact, lateral loading, slab area, shoring procedures, and so forth during concrete construction.

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APPLIED LOADS VERSUS LOAD EFFECTS

To provide design load values for construction that can be used in the design of formwork and other temporary support systems, information about the load effect rather than simply the applied load is required. This distinction is particularly important for buildings during construction. For these structures, all of the redundancies of the final structure are not yet in place, formwork systems are often much less stiff than the completed structure, and construction loads are often highly localized on the structure. The work by Ayoub and Karshenas (1994) used survey and inventory methods to collect data on the actual loads applied to formwork both before and after concrete placement. Fattal (1983) collected similar information on applied loads keeping extensive written and photographic records. However. adequate characterization of the applied loads, including spatial correlation (Karshenas and Ayoub 1994), may not be sufficient to describe the actual load effect experienced by the shores. The concept of an "influence surface" was employed by Karshenas and Ayoub (1994) to develop equivalent uniformly distributed loads that produced the critical load effect in the shores. However, owing to simplifications in the structural model, this approach is unable to account for discontinuities in the formwork, variable installation procedures, and other actual site conditions. Studies by Yen et al. (1995), Peng et al. (1996), and Rosowsky et al. (1995a) have all shown that these can have significant effects on the actual shore loads, and that the spatial variability associated with load effect can be much greater than that associated with the applied loading.

As an alternative to developing more complex structural analysis models, actual shoring load measurements can be taken to provide much-needed information on magnitude and variations in load effect. In addition, this information can be used to develop a relationship between the applied loading (i.e., actual loads on the slab) and the shore load effect, thereby providing information on load-structure interaction. A summary of recent and ongoing projects in which actual shore load data is being collected is presented in Rosowsky et al. (1994b).

DESCRIPTION OF BECKLEY, W. VA. SITE

The first site at which extensive data were collected was a low-rise concrete prison facility under construction in Beckley, W. Va. (Huston et al. 1996). The observations described in this paper are based on the data collected from this site. Two spe-

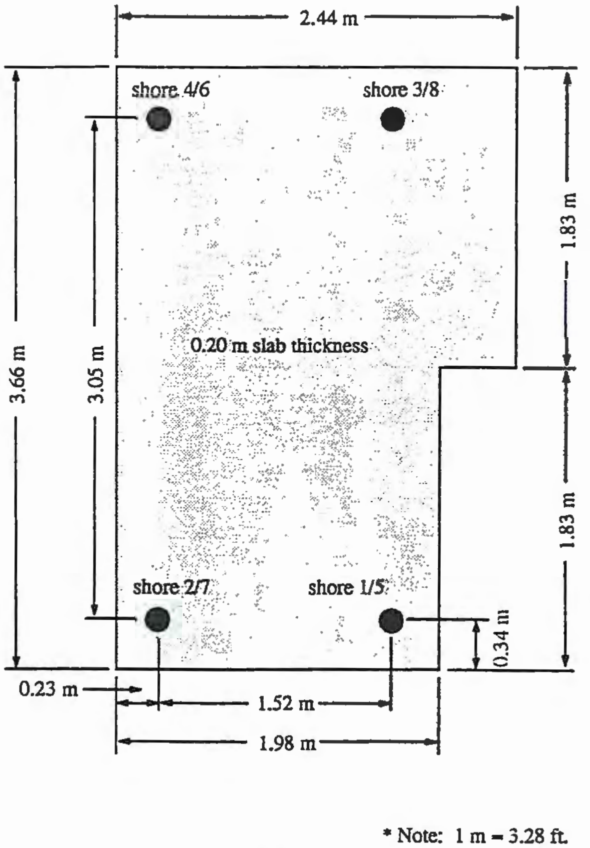

FIG. 1. Layout of Small Pour Area at Beckley, W. Va.

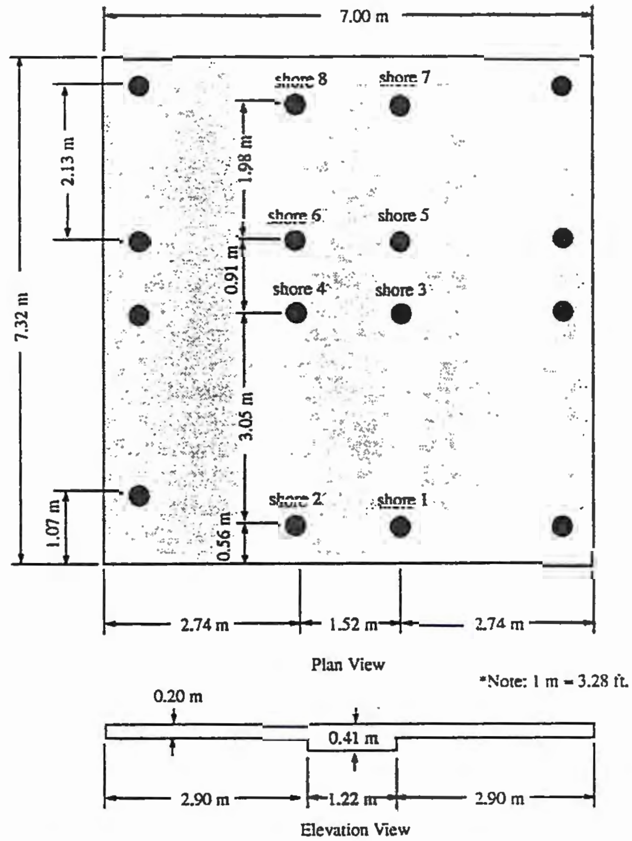

FIG. 2. Layout of Large Pour Area at Beckley, W. Va.

cific locations were instrumented and loads were monitored prior to placement of the concrete slab, during concrete placement, and after the slab was completed. Only shoring data were collected since reshores were not used. Two small pour areas were instrumented at the Beckley site. These areas, shown in Fig. 1, were identical 0.2 m (8 in.) thick slabs with pour areas of approximately 8.10 m^2 (87 ft^2). Since these areas were small, only four steel shores were used for vertical support during the pours. All four shores were instrumented for each of the small pour areas. Two steel I-beams were used to support the forms in each of the small pour areas. These I-beams spanned from shores 1/5 to shores 3/8 and from shores 2/7 to shores 4/6 (see Fig. 1). The steel I-beams supported wooden stringers that in turn supported the plywood forms.

The large pour area was approximately 51.28 m^2 (552 ft^2) and vertical support was provided by 16 steel shores. The slab thickness was 0.2 m (8 in.) and 0.4 m (16 in.), as shown in Fig. 2. Steel I-beams were used as the primary support for the 0.4 m (16 in.) slab thickness section. Four I-beams were used to span between shores 1-2, 3-4, 5-6, and 7-8 (see Fig. 2). The I-beams supported aluminum I-beams that spanned the 7.32 m (24 ft) length of the large pour area. Aluminum I-beams were also used to span from these members to two exterior steel I-beams also spanning the 7.32 m (24 ft) length, thereby providing support for the 0.2 m (8 in.) thick slab sections. Only those shores indicated in Fig. 2 were instrumented during the large pour.

DATA COLLECTION, REDUCTION, AND ANALYSIS

The data collected at the Beckley site included vertical and lateral shore load effects (one vertical and two lateral load channels per instrumented shore) during both the pouring and curing phases for each pour area. The sampling frequency for the pouring data was 100 Hz. This permitted the collection of sufficient data for later dynamic load analysis. Since the pour durations were several minutes, the data files were typically too large to be manipulated efficiently. For the purposes of data analyses, the data sets were reduced to more manageable sizes by stripping nine out of each 10 points from the raw pour data. The effects of this data reduction were not noticeable during graphical comparisons (i.e., no load spikes were lost), however this information might need to be reincluded for any dynamic analysis. Although the curing data were sampled at a lower frequency, similar reductions were performed to maximize efficiency during data analyses.

The load effect data were zeroed from the beginning of the individual pours. This procedure provided the load effects due to the pour only, thereby neglecting any residual prepour loads applied to the shores. The lateral load effects were compared to the vertical load effects for each shore and graphical representations of the two were examined to determine the existence of any correlation between them. Additional work included statistical analyses to determine time-dependent average load effects and load multipliers (which, when multiplied by the average shore load at a given time step, give the actual shore load). Design loads for the shoring members were also determined using published values and procedures [i.e., American Concrete Institute (ACI) codes] and compared with the measured load effects.

ANALYSIS

Lateral load effects in the shores were examined first. Consideration was given to (1) the relative magnitude of the horizontal loads; and (2) the correlation of horizontal loads with vertical loads. Provisions for horizontal design loads for construction are particularly limited. It is, however, widely believed that lateral instability is the primary cause of most formwork collapses. Fig. 3 shows the lateral load effects (in one direction) for the small pour area as a percentage of the vertical load acting at the same time. The pouring activities occurred approximately between minutes 15 and 30. As Fig. 3

suggests, when the majority of the vertical load is already applied, the lateral load is about ±10% of the corresponding vertical load. While percentages are somewhat higher earlier during the pour activity, this corresponds to points at which the actual vertical load is low; thus, the lateral load effect would not be large. Nearly identical trends were observed in the other lateral direction as well as for both lateral directions for the large pour area. This value of ±10% provides a simple guideline for approximating lateral loads on formwork.

Vertical loads were examined next. Fig. 4 shows the vertical load in the four shores used in one of the small pour areas. Values are shown for the entire construction activity process, including activities on the slab just prior to the concrete being poured, the actual concrete pouring operations, and a small amount of postpour activity. By considering the load traces as they reach their maximum values (i.e., toward the end of the pouring activity), along with the average values, some indication of the relative variability in shore loads (i.e., variations shore-to-shore) can be obtained. Recall that these four shores are part of the same single scaffolding unit and are therefore quite close together. To more clearly examine this variability, the ratio of individual shore load to average shore load was calculated and is shown in Fig. 5. Only the actual pouring process is shown (i.e., significant applied loads) starting at minute 18. Fig. 5 clearly indicates both the relative variability shore-to-shore and the variations of shore loads from the time-dependent average shore load. A shore load multiplier (vertical axis) of 1.0 at the end of the pour would imply that a simple tributary area analysis would be adequate for assigning portions of the total applied load to the individual shore. Fig. 5 indicates that shore load multipliers in excess of 2.0 were seen in this case.

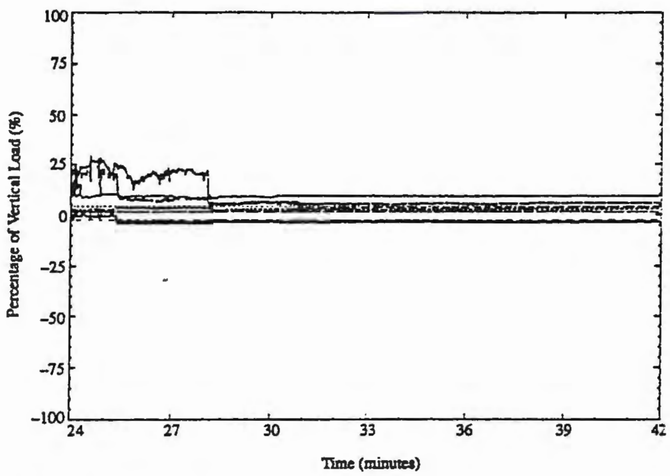

FIG. 3. Small Pour Lateral Loads (*y*-Direction) As Percentage of Vertical Shore Loads

Fig. 6 shows a detailed load trace (for the actual pour activity that occurs in the first 24 min) of the maximum of the four vertical shore loads in the small pour area along with the average shore load trace. Also shown in Fig. 6 are two possible design load values, the ACI design load and the tributary area load. The ACI design load (see "Building" 1989; "Guide" 1988) is the minimum load suggested by ACI, including concrete and equipment, for the actual slab area. ACI specifies a minimum design dead load of 41.32 N/m^2 (100 psf) for supported slab areas when designing vertical shoring members and shoring placement. This load corresponds to the dead load that would be produced by 0.2 m (8 in.) slab thickness. If the slab thickness exceeds 0.2 m (8 in.), the design dead load should be increased appropriately. In addition, ACI specifies an increase of 20.66 N/m^2 (50 psf) to account for live loads, material storage, impact effects, and so forth. The tributary area load shown in Fig. 6 is simply the estimated weight of the completed concrete slab divided by the controlling tributary area for the shores. The tributary area load for each pour was calculated based on the shore that had the largest area of slab to support. For example, the large pour area had many different shore tributary areas, but shores 1 and 2 supported the largest areas. Each of these shores supported a total slab tributary area of 4.44 m^2 (47.83 ft^2), corresponding to a dead

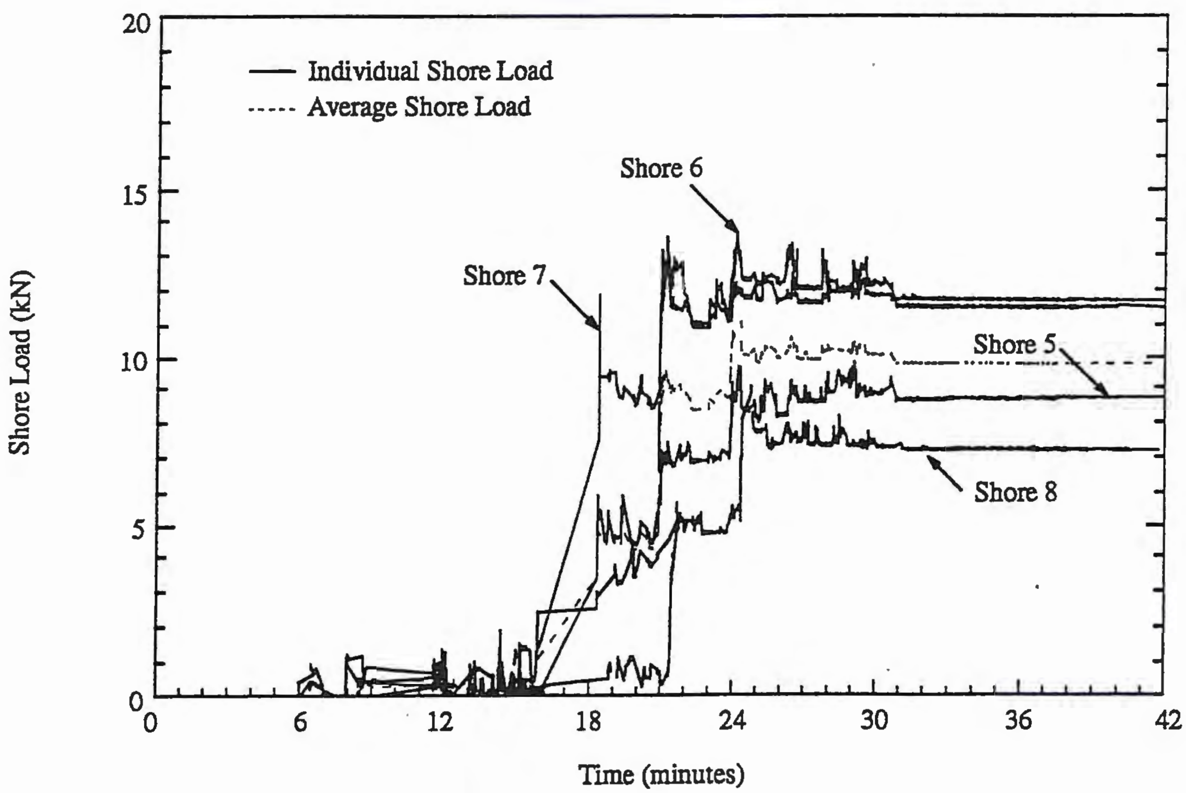

FIG. 4. Small Pour Individual Vertical Shore Loads

load of 27.4 kN (6,150 lb). The design load is therefore simply the tributary area dead load for the shores with an additional loading of 20.66 N/m^2 (50 psf) to account for live loads, material storage, impact loads, and so forth. The additional loading produces a design load, in the cases of shores 1 and 2, of 38.0 kN (8,540 lb). Note in Fig. 6 that the ACI design load is very close to the maximum shore load, and the tributary area load is very close to the average shore load. Fig. 7 shows the period following the pouring activity (i.e., early curing activity) for the two adjacent small pour areas. Note that this graph covers a time period of nearly three days. During this time, relatively little load was applied to the slab. However, the individual load traces exhibit slight variations on an essentially daily cycle. This graph also illustrates the relative variability among the shore loads and their magnitude relative to the ACI design load.

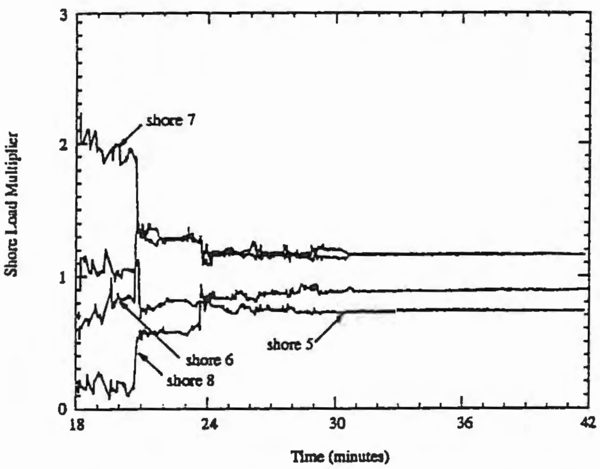

FIG. 5. Small Pour Vertical Shore Load Multipliers

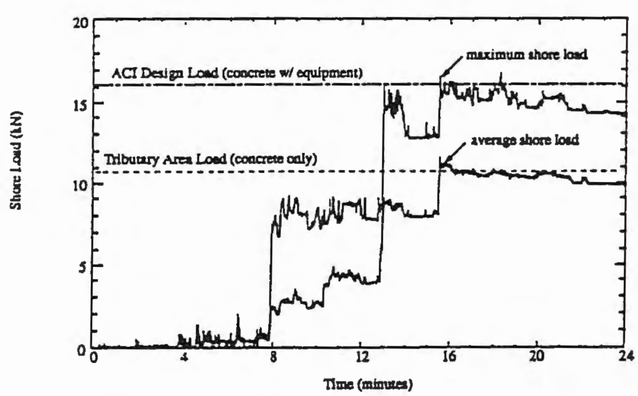

FIG. 6. Small Pour Vertical Shore Loads during Pouring

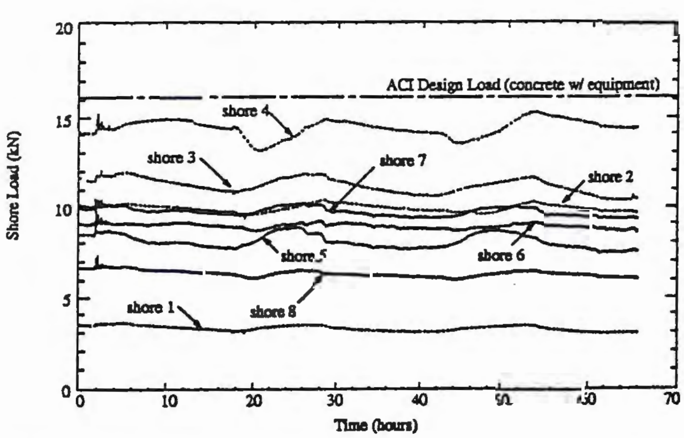

FIG. 7. Small Pour Individual Vertical Shore Loads during Curing

Figs. 8 and 9 present data obtained from the larger pour area. Fig. 8 shows a detailed load trace (for the actual pour activity that occurs in the first 48 min) of the maximum of the eight vertical shore loads in the large pour area along with the average shore load trace. Also shown in Fig. 8 are the two possible design load values described previously. In this case, the tributary area design load (concrete only) appears to be adequate for the maximum shore load, while the higher ACI design load (concrete and equipment) overestimates the actual maximum shore load by about 35%. Since the slab thickness, formwork, and placement procedures are all comparable, this is evidence of a possible area effect. That is, as the effective area increases, currently suggested design loads become more conservative. This may suggest the use of a construction load reduction factor for large pour areas, similar to the live load reduction factor in *ASCE 7–93* ("Minimum" 1993). Fig. 9 shows the period following the pouring activity (i.e., the early cure period) for the large pour area. This graph also illustrates the relative variability among the shore loads and their magnitude relative to the ACI design load. During this time, relatively little load was applied to the slab. However, the individual load traces exhibit definite variations on an essentially daily cycle. These daily fluctuations are much more pronounced than they were for the smaller area. Since no significant loads were being applied or removed during this period, the fluctuations in shore loads must be a result of changes in the ambient environmental conditions at the site. Being early fall in West Virginia, daily temperature variations can be substantial. During the actual instrumentation period, differences in temperatures from day to night varied by about 17°C (30°F). Steel shores will expand and contract significantly under a

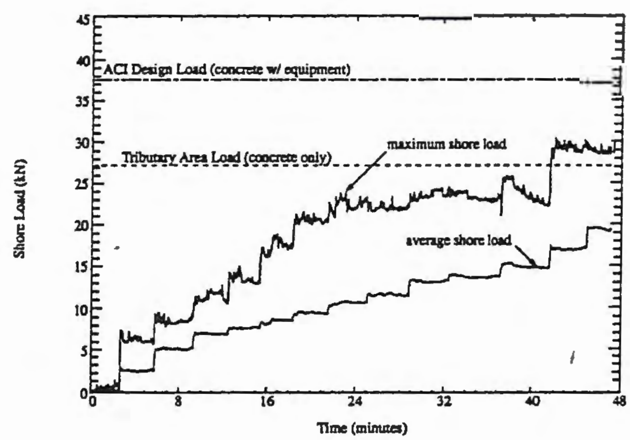

FIG. 8. Large Pour Vertical Shore Loads during Pouring

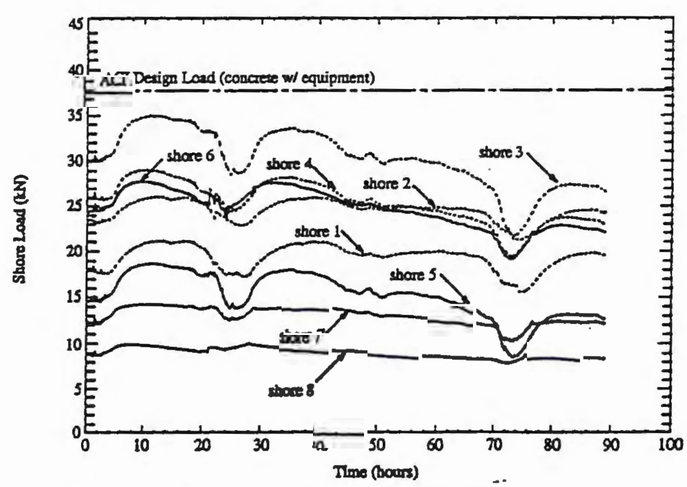

FIG. 9. Large Pour Individual Vertical Shore Loads during Curing

17°C temperature gradient. Assuming a steel shore (typical) with a diameter of 4.32 cm (1.70 in.), wall thickness of 0.28 cm (0.11 in.), and a shore length of 183 cm (72 in.), the calculated difference in shore length due to thermal expansion would be 0.036 cm (0.014 in.). The change in load carried by a shore would be related to its length (or change in length) by the relationship $\Delta L = (\Delta P)L/AE$, where ΔL = change in length of the shore; L = original length of the shore; A = cross-sectional area of the shore; E = elastic modulus of the steel; and ΔP = the calculated change in shore load due to the temperature gradient. For this case, the value of ΔP was found to be 13,834 N (3,110 lb). As seen in Fig. 9, changes in shore load of up to 6 kN (1,350 lb) were recorded; the difference between the predicted and the observed values may be the result of load sharing.

In addition to these daily fluctuations in load, many of the shore loads in Fig. 9 exhibit a general decreasing trend with time. Since relatively little load was applied to the fresh slab during this early cure period, and certainly no significant load was removed, this decrease in shore load is likely a function either of creep effects in the concrete or gain in strength and stiffness of the slab. The actual mechanism leading to this apparent decrease in shore load remains to be investigated. However, it is likely that the explanation for this phenomenon will also provide some insight into the evolution of the fresh slab, with essentially no load-carrying capabilities, into a structural element that is carrying part of its self-weight in addition to applied loads. This information may be useful in determining safe shore removal times.

Additional Investigation

To further investigate the possibility of a load reduction, the data collected by Fattal (1983) from a multistory flat-plate-type concrete building were considered. The effective slab area (pour area) was similar to that of the large pour area from the Beckley site; however, the design loads (which are functions of the pour area and the slab thickness) were roughly halfway between the values for the small and large Beckley pour areas. While the sampling frequency used by Fattal (1983) was far lower than that used in the Beckley investigation, and the data were available only in analog rather than digital form, sufficient information existed to develop figures such as those described previously. Fig. 10 presents the actual shore load data for one pour area along with the average shore load trace. One shore in particular exhibits much higher loads than the others, beginning very early in the concrete placement process. This is likely due to some deficiencies in the shore installation. Even before half of the total slab load is placed on the formwork, the load in that shore is far in excess of the ACI design load. The tributary area load is slightly conservative relative to the average shore load. Disregarding the shore with the very high loads, the ACI design load closely predicts the maximum shore load.

Comparing the results from the Beckley site (Figs. 6 and 8) with those from Fattal's (1983) study (Fig. 10) suggests that a load reduction effect may indeed exist but may not simply be a function of the pour area. Rather, a load reduction may be appropriate for certain cases as a function of pour area, slab thickness, formwork arrangement, and perhaps method of placement. Collection of data from additional sites and analytical investigations (structural modeling) are required in order to examine this issue further. Both of these are planned as part of this project and the results are expected to be reported in the next year.

Shore Removal

Shore removal procedures can induce significant loads, often of an impact nature, on both the supporting formwork elements and the freshly cast slab. The magnitude of these loads is a function of amount for compression in the shore at the time of removal and the procedure used for the removal of that shore. In some cases, this may involve knocking out the shore or the shims with a hammer, while in others it may be accomplished by first slowly relieving the compression in the shore. As part of the data collection activity at the Beckley site, shore loads were recorded during the removal of the eight shores in the large pour area. Fig. 11 shows the shore loads and clearly indicates when the individual shores were removed. Also shown in Fig. 11 are the tributary area load (concrete only) and the ACI design load (including provisions for equipment). The locations of the numbered shores are shown in Fig. 2.

As can be seen from Fig. 11, the loads resulting from shore removal take two forms: (1) additional compression in the shore as part of the actual removal procedure; and (2) load redistribution to remaining shores following shore removal. When the first shore was removed (shore 4), only shore 6 saw a significant increase in load. As seen in Fig. 2, these two shores were very close to each other. Note also that with this redistributed load from shore 4, the load in shore 6 increased above the tributary area load. When shore 2 was removed, the majority of its load appears to have been picked up by shore 5. Note (Fig. 2) that these two locations are not very close to one another. When shore 1 was removed, shore 6 was the only shore to see a significant increase in load. Even though two other shores were still in place (7 and 8), they were on the

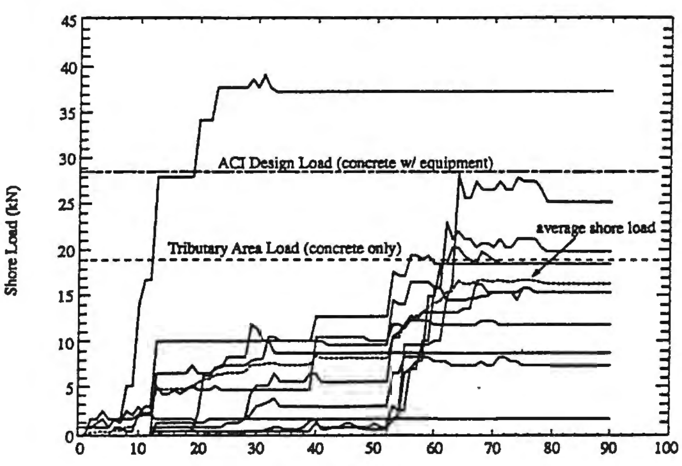

FIG. 10. Vertical Shore Loads during Pouring (Data from Fattal 1983)

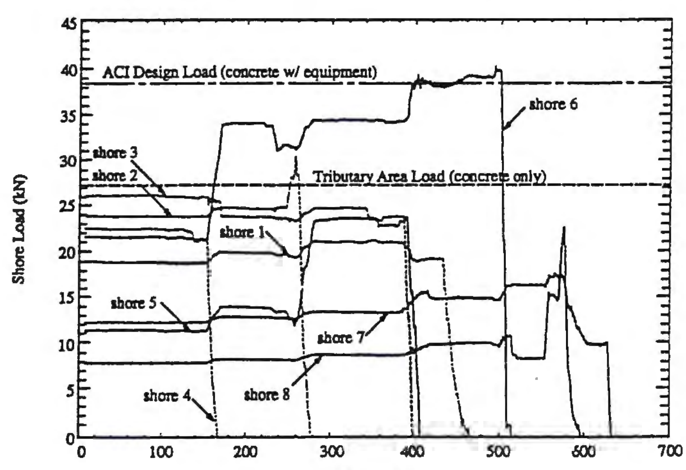

FIG. 11. Large Pour Individual Vertical Shore Loads during Shore Removal

other side of the slab; hence there was limited load sharing (redistribution). At this point, the load in shore 6 was very close to the ACI design load. Finally, when shore 6 was removed, its load was picked up entirely by the slab (i.e., shores 7 and 8 did not see significant increases). In effect, a 40 kN (8,990 lb) load was applied nearly instantaneously to the fresh slab at shore location 6, near the center of the slab. The potential for increase in load as part of the shore removal operation is illustrtated by the removal of shores 2 and 8. When shore 2 was removed, the load increased by about 25%. The removal of shore 8, which appears from Fig. 11 to have been a two-step process, resulted in an increase in shore load of more than 250%. Clearly, the procedure used to remove shores can significantly affect the shoring (and slab) loads and hence the safety of the structure during construction.

CONCLUSIONS AND IMPLICATIONS FOR DESIGN LOADS

A preliminary analysis of shore load data collected during actual concrete construction has been performed and a number of significant observations have been made. These observations shed new light on the load sharing behavior of formwork systems, identify potentially hazardous procedures and conditions during concrete operations, and can be used to assess the adequacy of current construction design loads (i.e., those suggested by ACI). Specific findings reported herein include:

1. The observed lateral shore loads were typically on the order of $\pm 10\%$ of the corresponding (i.e., simultaneous) vertical load.
2. A magnification factor on the order of 2.0 may be appropriate to account for the (spatial) variability among a group of shores in a common pour area. The degree of variability shore-to-shore appears to be a function of the amount of precompression imparted during installation.
3. The suggested ACI design load, including equipment, appears to be adequate for the slab areas considered in this study. The simpler "tributary analysis" design load well approximates the average shore load, while the more conservative ACI load (including equipment) well approximates the maximum shore load. However, an error in the installation of a shore can result in that shore being seriously overloaded.
4. An area-effect may exist that serves to reduce the maximum shore load for a given pour area (i.e., the ACI design load becomes more conservative as the effective slab area increases). A reduction in design load for construction may be a function of pour area, slab thickness, formwork arrangement, and concrete placement procedures.
5. Significant load variations in steel shores may result from large daily (or other) temperature variations. These variations were particularly evident during curing periods, even when there were no additional externally applied loads.
6. A small decrease in shore load was observed during the curing period. This decrease in shore load is likely a function either of creep effects in the concrete or gain in strength and stiffness of the slab. The decrease in load appears to become greater with increasing effective slab area.
7. Shore removal can induce significant loads on the slab and shores, often of an impact nature. The magnitude of these loads is a function of the amount of compression in the shore at the time of its removal and the removal procedure used. Shore removal loads take two forms: (1) additional compression due to the removal procedure; and (2) load redistribution following the removal of a nearby shore. The amount of load redistribution is largely a function of the supporting formwork arrangement. Very large effective impact loads may be imparted to the (early age) slab during formwork removal.

The work described herein is part of an ongoing effort to collect load data during concrete construction and the observations are based only on a limited amount of shore load data. However, it is apparent that a great deal can be learned even from a qualitative analysis of this valuable information. As additional sites are monitored and data are collected and analyzed, much needed information will become available on which to base construction design loads. This, in turn, will lead to improved safety of buildings and temporary formwork systems during construction.

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