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Modeling of Fresh Concrete in Precast Box Culvert Mold Under Vibration

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Abstract: ***The goal of this study is to specify the criteria of computer-aided design of formwork employed in the production of precast concrete elements. For this aim, modeling of fresh concrete was performed to solve the problem of the effect of vibration applied on the steel mould during production and fresh concrete-mould dynamic interaction. The study included both experimental and theoretical components. The experimental part was realized at the production plant of Kambeton Company. The theoretical part was executed using Finite Element Method employed in SAP2000 software. The computational results of displacement histories were compared with the experimental ones.***

Keywords: Prefabricated concrete structure, Test measurement, Vibration, Modeling of fresh concrete, Fresh concrete-mold interaction

1. Introduction

External vibrators are widely used in manufacture of prefabricated concrete members. Vibration transmitted to the concrete formwork by the vibrator's run also vibrates the fresh concrete within the mold.

There are a limited number of numerical and/or test works in the literature on the attitude of fresh concrete under vibration. Most works indicate that fresh concrete is not a Newtonian fluid in the quiescent state and conforms to the Bingham model.

Tattersall and Baker [1] demonstrated the flux attitude of fresh concrete without vibration using following Bingham model.

$$\tau = \tau_o + \mu \dot{\gamma} \qquad (1)$$

Where, τ is shear stress, τ_o is yield stress, μ is plastic viscosity and $\dot{\gamma}$ is shear rate.

Larrard et al. [2], employing an apparatus named ‘BTRHEOM’, stated that the yield stress of fresh on concrete was halved under vibration, and in some statuses approached zero, and also that the plastic viscosity value was not influenced by vibration.

Alexandridis and Gardner [3] experimentally studied the shear strength characteristics of fresh concrete employing a triaxial pressing tool. The test results were analyzed using Mohr-Coulomb and Rowe shear strength models. The "angle of internal friction" of fresh concrete, analyzed using the Mohr-Coulomb theory, was discovered to be a fixed feature of concrete mix between 37° and 41°. When analyzed using the Rowe theory, it was found to be between 18° and 21°. Both theories indicated that the cohesion of fresh concrete was initially zero and increased with time as the concrete hardened.

The "Poisson's rate" of fresh concrete was expressed as an equation in a computer program named HIPERPAV published by the U.S. Department of Transportation [4]. In the plastic state, the Poisson's ratio was found to be between 0.40 and 0.45. The Poisson's ratio as a function of time is expressed as in equation (2).

$$\nu(t) = -0.05 \ln(t + 1.11) + 0.425 \leq 0.42 \qquad (2)$$

Where t is time elapsed after the concrete was prepared (hours).

Wenzel [5] noted that external vibrator vibrations employed for concrete compression in precast structural element generation generally cannot reach a penetration depth greater than 20 cm. Therefore, for sections greater than this, the vibrators must be attached to both sides. It was observed that applying a cyclic frequency of 50 Hz to the mold caused "segregation" due to the large amplitude. This led to the view that higher frequencies should be exposed to the concrete to achieve a good compression impact. Optimal frequencies for this goal were specified to be between 75 and 200 Hz.

Determining type and location of vibrators used in prefabricated structural elements through trial-and-error methods is time-consuming and does not always yield optimal results. Therefore, computer-aided formwork design is required, and the multi-degree-of-freedom structural system containing steel formwork and fresh concrete must be modeled and dynamically analyzed. The "Mode Combination Method" is commonly used for dynamic analysis.

Wilson et al. [6] used Ritz vectors and Eigenvectors in Dynamic Mode Combination analysis and applied their comparisons on some example structures.

This study compares the time-dependent lateral displacement values obtained experimentally and theoretically at selected points on the steel mold surface vibrated by external vibrators to form the basis for the computer-aided design of steel molds used in prefabricated structural element production.

The experimental part of the study was conducted at the Kambeton Company’s production facilities in Adana, using

100 Hz (revolutions/sec) external vibrators. Numerical piece was done with the Finite Element Method using SAP2000 [7] computer software.

The study is significant in that it provides a validated modeling approach for predicting mold behavior under vibration, which can streamline formwork design, enhance production efficiency, and minimize material waste in the prefabrication of concrete elements.

This paper aims to develop and validate a computational model that simulates the behavior of fresh concrete in precast box culvert molds under vibration, by comparing experimental results with numerical analysis using SAP2000.

2. Experiments

Tests were made on surface of formwork for prefabricated concrete constructive members by using a data acquisition system. Experiment set-up used in study is represented below.

2.1. Hardware

Related parts in articles:

a) Dynamic Strain Meter, DA-32D type (Tokyo Sokki Kenkyujo Co., Ltd.)
b) LVDT (Linear Variable Differential Transformer, Displacement Transducer)
c) ISC-16 PCI Data Acquisition Card (RC-Electronics, Inc.)

2.2. Software

SIGNALYS Program (Ziegler-Instruments GmbH, Germany, 1990)

2.3. Experimental setup

The calibration of LVDT was done usage a dial gauge that has the sensitive of 1/100 mm. Displacements obtained by transducer have been saved in the same time with 0.5 ms sample rate in 4.096 sec.

The specifications of the external vibrators used in production are given in Table 1.

Table 1: Clamp-on vibrator's properties

Mechanical Properties					Electrical Properties	
Vibrat. range	Centrifugal force		Weight	Max. input power	Max. current A	
Vibr./min	kg	kN	kg	W	42V	250V
6000 (200 Hz)	1157	11.34	25	1200	23	-

The mold is made of steel plate 5 mm in thick. Steel sections in diverse dimension and section are attached to mold in horizontal, vertical and diagonal ways to power of system.

Mold's plan view and the coordinates of the points where the measurements were taken are illustrated for box element in Fig. 1.

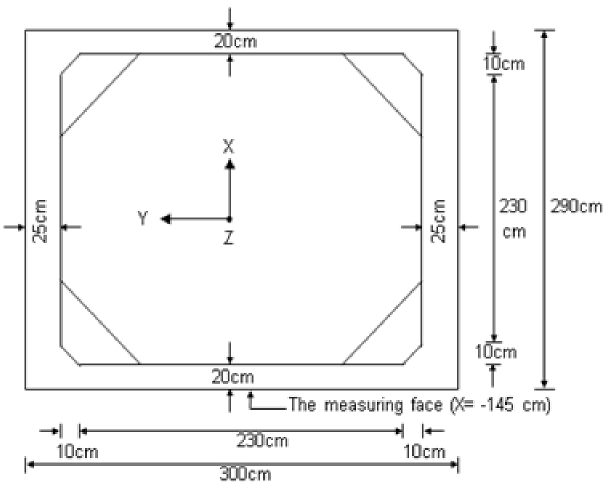

Figure 1: Plan view of the box culvert formwork (h = 97 cm)

3. Modeling of empty box culvert formwork

The equation of motion of a structural system with N degrees of freedom modeled with a finite number of elements can be written in terms of nodal displacements as

$$\mathbf{M}\,\ddot{\mathbf{u}} + \mathbf{C}\,\dot{\mathbf{u}} + \mathbf{K}\,\mathbf{u} = \mathbf{P}(s,t) \tag{3}$$

Where **M**, **C** and **K** NxN dimensional mass, damping and stiffness matrices of the system, $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$ and $\mathbf{u}$ and P(s, t) are the Nx1-dimensional time-dependent acceleration, velocity and displacement vectors of the system, respectively, and P(s, t) is the Nx1-dimensional load vector that varies with location and time.

The system equation of motion is solved in the time domain using the mode combination method. The mode vectors used can be either eigenvectors or load-dependent Ritz vectors.

Mold bodies for the box culvert prefabricated structural element are manufactured from 5 mm thick sheet steel. Additionally, steel sections of different sizes and cross-sections are attached horizontally, vertically, and diagonally to reinforce the mold. Therefore, the molds are constructed from shell and bar elements. Depending on the geometry, shell finite elements are constructed from four-node square, rectangular, trapezoidal, and three-node triangular elements with dimensions of approximately 10x10 cm. The bar elements are obtained by using common nodal points with the shell elements.

The three-dimensional finite element mesh of the box culvert formwork is presented in Fig. 2.

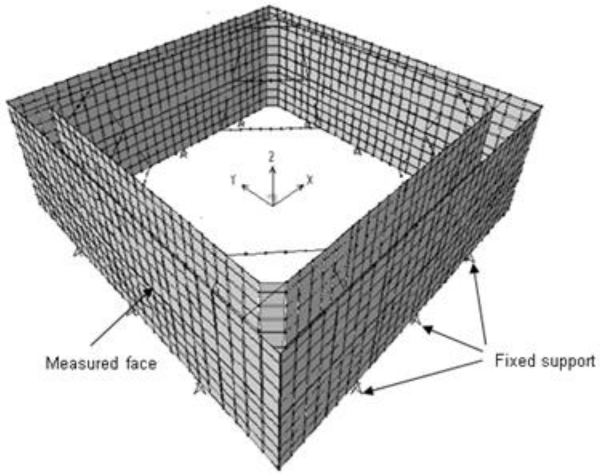

Figure 2: 3-D view of box culvert formwork

3.1. Load applied by external vibrators to box culvert formwork

External vibrators, attached to the mold surface

$$P(t) = P_o \sin(\omega t) \quad (4)$$

Worth, applies a sinusoidal dynamic load perpendicular to the surface.

Where, P_o is amplitude of load, ω is forced frequency, t is time

The period (T) and cyclic frequency (f) of the load are expressed in terms of angular frequency.

$$T = \frac{2\pi}{\omega}$$

$$f = \frac{\omega}{2\pi} = \frac{1}{T} \quad (\text{Hz}) \quad (5)$$

can be written. The vibrators are attached to a 20x25cm rigid plate and fixed to the mold surface by this plate. In the analyses conducted on the empty mold in this study, it is assumed that the vibrator load acts as a uniformly distributed compressive load on the shell element faces in touch with the plate to which vibrator is connected.

4. Modeling of box culvert mold while filled with fresh concrete

Fresh concrete poured into the mold significantly alters the mold behavior compared to the empty state, and the fresh concrete-mold interaction must be considered in patterning. For this goal:

a) Fresh concrete enforces a pressure force on mold surface, the intensity of which varies depending on time and location,
b) The concrete mass can be defined as a large number of point masses concentrated at the nodes on the formwork surface, is accepted.

Modeling of the mold and vibrator load is the same as for the empty mold.

4.1. Compressive force exerted by fresh concrete to formwork

Compressive load applied to the mold by fresh concrete, in the shape of equation (6) is given below.

$$P(s, t) = b(s).w(t) \quad (6)$$

It is expressed as the product of two functions that depend on location [b(s)] and time [w(t)]. These functions are defined below.

4.1.1. Function b(s) dependent on location

The function b(s) displays the lateral static pressure enforced by the non-solid fresh concrete on the formwork,

$$b(s) = K_o \gamma h \quad (7)$$

$$K_o = 1 - \sin\phi \quad (7a)$$

$$K_o = \nu / (1 - \nu) \quad (7b)$$

is defined by the expressions. Where,

b: Static lateral pressure (force/area),
K_o: Lateral pressure coefficient,
γ: Specific weight of the material,
h: Hight,
ϕ: Internal friction angle of the material,
ν: Poisson Rate of the Material,

K_o is a coefficient varying between 0 and 1 and is expressed in two various ways: depending on the internal friction angle of the material as seen in equation (7a) or depending on the Poisson Ratio of the material as in equation (7b).

The actual circulation of static lateral pressure along the mold height is shown in Figure 5a. Assuming that the mold is divided into n shell elements along the height, the uniform pressure load values to be applied to each element are calculated as explained in Figure 5b.

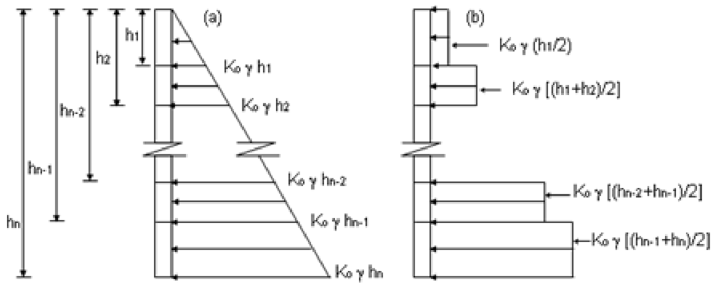

Figure 3: (a) Actual circulation of lateral pressure, **(b)** Simulation of lateral pressure

4.1.2. Time-dependent function w(t)

In order to determine the change in pressure enforced by fresh concrete on formwork surface over time during the vibration process, the experimental measurement results performed while the mold was empty and full were evaluated. The w(t) function, which expresses the change in the reaction force created by the fresh concrete on the surfaces modeled in this way, was chosen as a periodic function as seen in Fig. 4. θ shows the phase difference between the vibration load and the concrete response.

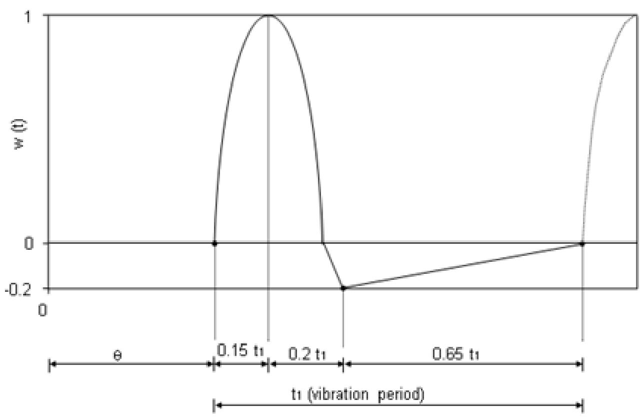

Figure 4: Variation of the function w(t) with time

5. Implementations

In this section, the findings obtained from the experimental and theoretical studies carried out on the steel mold used in the production of prefabricated box culvert by Kambeton company, while the mold was filled with fresh concrete, is presented and evaluated. While there is significant irregularity in the initial phase of dynamic behavior, this quickly disappears and attitude becomes regular. Therefore, graphs are presented for a typical time period during which attitude is regular. Theoretical analyses were performed using the SAP2000® software package. The number of vibration modes in the analyses was determined based on the cumulative mass participation ratios of construction in the global X, Y, and Z directions exceeding 90%. In all graphs, the positive directions of displacement are directed inward from the mold surface.

Some parameter values of the steel and concrete from which the molds are produced are selected as follows.

Specific weight of steel: $7.682\text{x}10^{-5}$ N/mm^3
Elasticity module of steel: 199948 N/mm^2
Poisson ratio of steel: 0.30
Specific weight of fresh concrete:2.45 t/m^3
Internal friction angle of fresh concrete (ϕ): 18°
Poisson ratio of fresh concrete: 0.40
Lateral pressure coefficient of fresh concrete (K_o): 0.75
Phase difference between vibration load and concrete response: 4.5 msn

5.1. Implementation 1

In this application, free vibration analysis was performed for box culvert formwork. The cyclic frequency values for the first six vibration modes of the formwork are shown in Table 2.

Table 2: Free vibration frequencies of the box culvert mold

Mod No	Box culvert form Frequency (Hz)
1	18.49
2	21.77
3	21.82
4	25.48
5	25.94
6	27.98

As can be seen from the examination of the frequency values, the most effective frequency values for the mold are much lower than the vibrator frequency of 100 Hz. Therefore, applying vibration to the mold using 100 Hz vibrators will not cause resonance or impair mold stability.

In this application, the contribution of Eigenvectors and Ritz vectors, which can be used as alternatives in the Mode Combination Method, to the cumulative mass participation ratio is investigated. The directional variation of the mass participation ratios based on the number of modes is shown in Table 3 for the box culvert form and in Table 4 for the column form.

As can be seen from the examination of the tables, the mass participation rates obtained using Ritz vectors are much higher than those obtained with Eigenvectors.

Table 3: Mass participation rates of the box culvert form

Mode numbers	Vector type	Mass participation rates (%)		
		X way	Y way	Z way
50	Eigenvector	29.08	31.03	0.005
	Ritz vector	**88.64**	**87.15**	**98.15**
100	Eigenvector	34.78	34.52	0.01
	Ritz vector	**96.05**	**95.87**	**99.17**
150	Eigenvector	35.54	37.18	0.05
	Ritz vector	**97.91**	**97.82**	**99.65**

5.2. Implementation 2

In this application, theoretical vibration analysis is performed for the box culvert form and the results are compared with experimental data.

Under the influence of an external vibrator located on the measuring surface of the box culvert mold, the change in displacement perpendicular to the mold surface was measured over time at point’s 1 and 2 (Fig. 5).

The Time History analysis of the box culvert formwork was conducted using ninety-five Ritz vectors. The initial Ritz vectors were the pressure load enforced by the vibrator to formwork, pressure load applied by the fresh concrete, and the acceleration vectors on the global axis. The formwork vibration parameters are shown in Table 4.

Table 4: Vibration parameters of the box culvert mold.

Number of dynamic degrees of freedom	Cumulative mass participation rates (%) (Ritz vector number = 95)		
	X way	Y way	Z way
7353	95.67	95.44	99.11

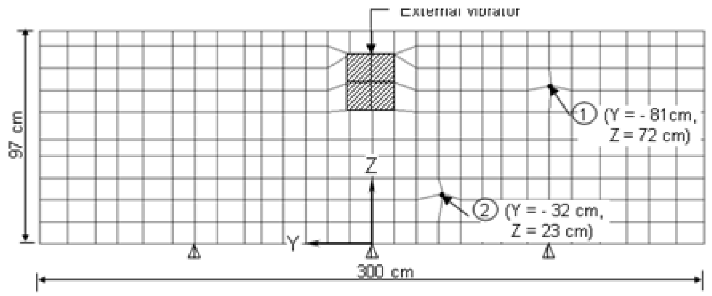

Figure 5: Measuring surface of box culvert formwork (Y-Z plane, X = -145 cm)

The change in displacement over time obtained theoretically at selected points for the formwork system is compared with experimental data obtained at the same points for a typical time period in Figs 6 and 7. Examination of the figures reveals that the theoretical and experimental results are in compatible.

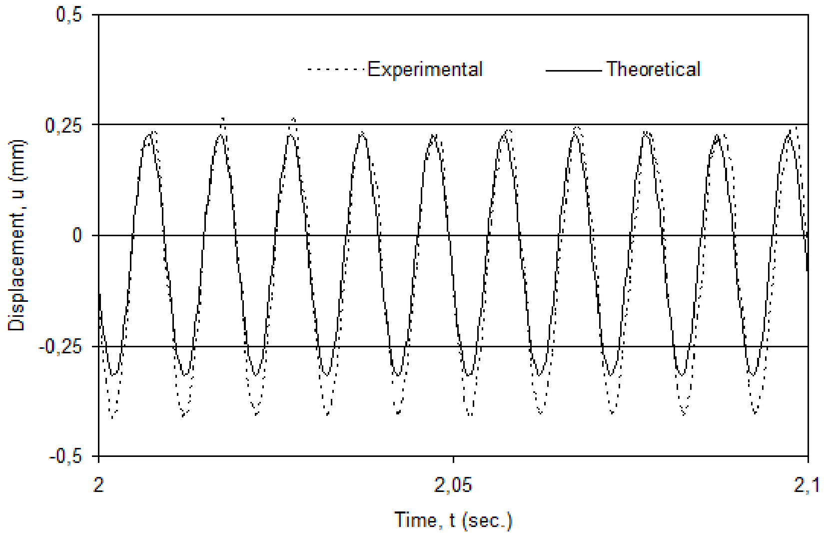

Figure 6: Variation of experimental and theoretical displacement on mold surface over time (Point 1)

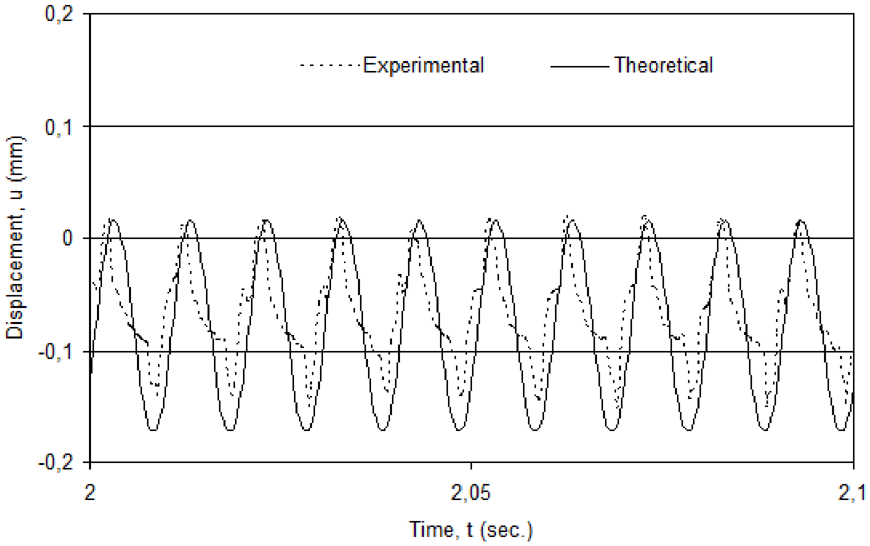

Figure 7: Variation of experimental and theoretical displacement on mold surface over time (Point 2)

6. Results and Discussion

Site tests on prefabricated structural elements manufactured using external vibrators were conducted at the Kambeton production facility in Adana using a data acquisition system. Tests were conducted on two different prefabricated structural elements by measuring the change in displacement perpendicular to the mold surface over time at selected critical points on the surfaces of the steel molds forming these elements.

A model for the fresh concrete-mold interaction was developed, taking into account the effect of fresh concrete when the mold is full. The values calculated using this model was compared with those measured experimentally, and the results were found to be consistent. This model has the potential to shed light on computer-aided mold design.

In dynamic mode coupling analysis, Ritz vectors significantly reduce the computational time (computer time) compared to Eigenvectors, provided the same number of modes are used; moreover, dynamic mass participation rates are significantly increased. Therefore, for complex mold systems with thousands of degrees of freedom, the use of Ritz vectors in dynamic mode coupling analysis is recommended.

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