Impact behavior of concrete beams with corroding reinforcing steel

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1. ABSTRACT

The paper describes an experimental and analytical investigation of the one-shot impact behavior of reinforced concrete beams subjected to varying periods of accelerated corrosion in seawater with induced current. The objective was to simulate long-term field corrosion and determine the reduction in structural integrity. An instrumented electromagnet-triggered dropweight system was used to determine the load and energy traces of beams supported on an isolation block. Three linear physical models, i.e. beam, two and three-degree-of-freedom spring mass, and a nonlinear finite element model, were used and the analytical energy and load values compared with those from the tests.

2. INTRODUCTION

Impact loads on land-based structures can be caused by hurricanes, gusts, earthquakes, collisions, or cavitation. Short-term impact loading may have catastrophic effects on corroded steel in concrete structures. Two modes of failure are possible under impact loading: local failure including penetration and perforation of the barrier, and overall structural failure. The behavior of reinforced concrete structures under impact can be predicted using constitutive relationships, failure criteria, and bond characteristics of concrete and steel over a wide range of strain-rates.

This paper describes the single-shot impact behavior of corroding steel reinforced concrete subjected to accelerated corrosion in seawater with induced current (Reddy et al 1986). The impact behavior is studied using three different approaches: i) an experimental investigation, ii) three physical models, and iii) a non-linear finite element model.

3. LITERATURE REVIEW

Different types of impact load tests were reviewed, and based on three types of failure modes it was concluded (Skov and Olsen 1974), that the observed resistance to impact could be accurately predicted based on energy considerations provided a flexural failure mode occurs. An extensive theoretical study of the beam impact problem, was carried out and good correlation obtained with data from instrumented dropweight impact testing (Hughes and Speirs 1982). A review of the analytical models was presented for high strain rate behavior of reinforced concrete (Suaris and Shah 1982). The finite element code, ADINA [Automatic Dynamic Incremental Nonlinear Analysis] was used to simulate the impact of reinforced concrete beams and compare the results with experimental values (Emrich, Herter, and Puffer 1982).

4. EXPERIMENTAL INVESTIGATION

Forty-six pin-ended reinforced concrete beams, 4" x 4" x 14" long, were subjected to impact using a centrally loaded instrumented dropweight impact system, Fig. 1. The impact was a one shot destructive blow from which energy and load measurements were taken. The dropweight system is an in-house design. It uses a weight and tup assembly weighing approximately 300 lb. The instrumented tup measures the compressive load interaction between the tup and the specimen during the impact event using two semiconductor strain gages. The power supply and amplification of the tup-load signal are processed using a dynamic response module (DRM) and a signal conditioner. The output, recorded through one of the horizontal channels of a dual-trace storage oscilloscope, gives the load and energy absorbed during impact, Figs. 2 and 3. The energy absorbed during impact gives a trace which is an

Fig. 1 Instrumented dropweight impact system

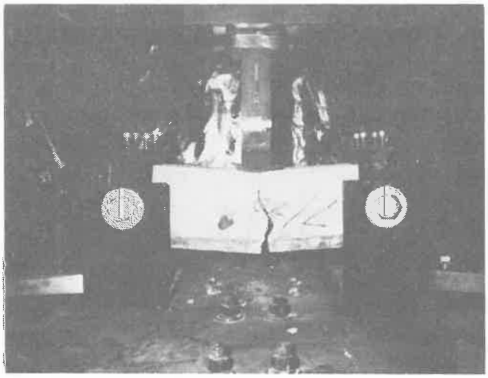

Fig. 2 Impact failure

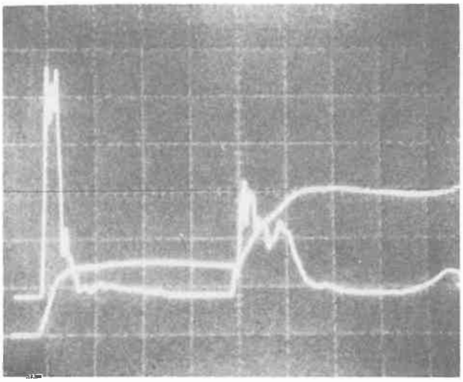

Fig. 3 Load and energy traces

integral of the load history over the time period multiplied by the velocity at impact:

$$E_{abs} = v_o \int p_o \, dt \qquad (1)$$

A special infrared flag assembly is used for triggering of the storage oscilloscope and for velocity measurement at impact.

To ensure proper failure of the specimen, the testing was conducted with an electromagnet-triggered weight of 300 lb. from dropheights varying from 1.0 ft to 2.5 ft corresponding to impact velocities of 9.63 ft/sec to 15.22 ft/sec. A 1/8 in thick rubber pad was introduced in the tup-specimen contact zone to reduce the inertial effects.

The expected reduction in failure load between the different sets of beams was not observed as inertial effects of the supporting isolation block were the major factors influencing the load sensed by the tup. This is also an indication that the energies can only provide comparative estimates. The evaluation of inertial effects would necessitate another set of experiments. The values for DE_o recorded in Table 2 represent the energy absorbed by a beam at the end of the elastic region of the impact. Based on a comparison of the above mentioned values, it is seen that the two-week corroded beams need an average 80.8% of the energy required by the one-week corroded beams for failure, while the three-week corroded beams need an average 73.3% of the energy at failure of the one-week beams.

From the mean and variance of the measured impact values, random numbers were Monte Carlo generated with specified confidence intervals to expand the data base. The mean and variance of this data were used to determine the Beta distribution function (very versatile for modeling the probabilistic behavior of phenomena constrained to a finite interval of possible values). These values reported by Reddy et al (1986) are not included in this paper for the sake of brevity.

5. ANALYTICAL INVESTIGATION

5.1 Beam model

A beam impact equation was developed (Hughes and Speirs 1982) by solving the equation of forced vibration for a pin-ended beam with center span impact. Free vibration modes were used in solving this equation for impact force, beam displacement, and energies during the impact.

It is assumed that the beam follows the Hertzian law of contact defined by

$$F(t) = K_c a^{3/2}(t) \quad , \qquad (2)$$

where a(t), the deformation at the impact zone, is expressed as follows:

$$a(t) = y_1(t) - y_2(x,t) \quad , \qquad (3)$$

K_c = deformation constant (stiffness of the impact zone),

and

y_1, y_2 = tup and beam displacements.

The impact equation is given by

$$(F/k)^{2/3} = vt - \frac{1}{M_t}\int_0^t d\bar{\tau}\int_0^{\tau} F(\bar{t})\, dt - \frac{2}{M_b}\sum_{i=1,3}^{\infty}\frac{1}{\omega_i}\int_0^t F(\bar{t})\sin(\omega_i(t-\bar{t})d\bar{t} \qquad (4)$$

where M_t = tup dropweight mass, M_b = beam mass, ρ = concrete density, τ = pulse duration, t = a value of t, and ω_i = ith circular frequency. A numerical technique has been described (Desnoyers 1987) to determine the impact force vs time history relationship.

5.2 Two-degree-of-freedom model

The simple two spring-mass system was used (Suaris et al 1980) to characterize a two-degree-of-freedom model, Fig. 4. Assuming that the supports are infinitely stiff as compared to the beam, expressions for equivalent spring and mass values are obtained for the first mode and the displacement responses, y_1 and y_2, determined. The load transmitted through the tup and the energy expended by the hammer are given below.

$$P_t(t) = K_c(y_1(t)-y_2(t)) + M_t g \quad , \qquad (5)$$

and

$$DE_o(t) = 1/2\ M_t(v^2 - (y_1(t)^2) \quad . \qquad (6)$$

where v = impact velocity and g = gravitational acceleration.

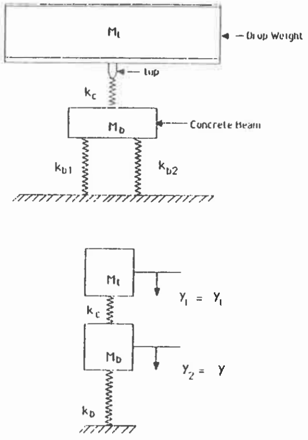

Fig. 4 Two degree-of-freedom model

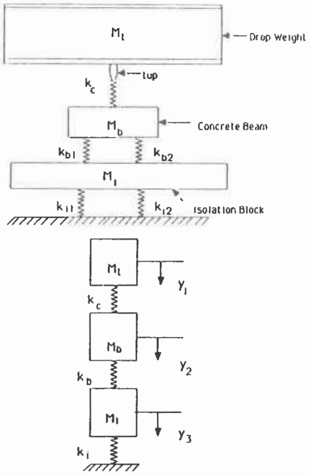

Fig. 5 Three degree of freedom model

5.3 Three-degree-of-freedom model

The three-degree-of-freedom model described below, Fig. 5, has been developed in an effort to represent more realistically the experimental setup used in this investigation. The tup load transmitted and the hammer energy expended are similar to Eqs. 5 and 6 above.

The results show that the beam model and the two-degree-of-freedom model give impact load histories which are very similar to each other in shape and magnitude. However, the three-degree-of-freedom model gave a failure load which is 55% of the load obtained from the beam model and 62% of the load obtained from the two-degree-of-freedom model.

5.4 Finite element idealization using ADINA

The finite element program, ADINA (ADINA Engineering 1981, 1983) was used to analyze the reinforced concrete beams. Four beam models, uncorroded, and corroded for one, two, and three weeks to simulate the four types tested experimentally. In this model, the amount of steel corrosion for the four different sets of beam specimens was simulated by reduced cross-sectional areas of steel reinforcement. The three periods of corrosion were approximate simulations of ten to thirty years of seawater exposure. This equivalence was established based on some available field data from Treat Island, Maine (Neill 1980).

Dynamic nonlinear analyses were performed on a model consisting of 79 elements and 181 two-degree-of-freedom nodes. Due to the symmetry of the structure and loading, a mesh of only one half of the beam was considered as seen in Fig. 6. The concrete part of the mesh was modeled by 50 eight-mode, two-dimensional plane stress elements. The material behavior is described by: i) a nonlinear stress-strain relationship which allows for shear softening, ii) failure envelopes which describe crushing in compression and failure in tension, and iii) a modeling strategy for post-cracking and crushing behavior. The multiaxial stress-strain relations are obtained from the uniaxial stress-strain relationship. The steel reinforcement was modeled by 29 three-node elastic-plastic isotropic nonlinear truss elements. Four different amounts of reinforcement were used in the dynamic analyses. Different time function inputs, obtained experimentally, were used for the uncorroded and corroded beams.

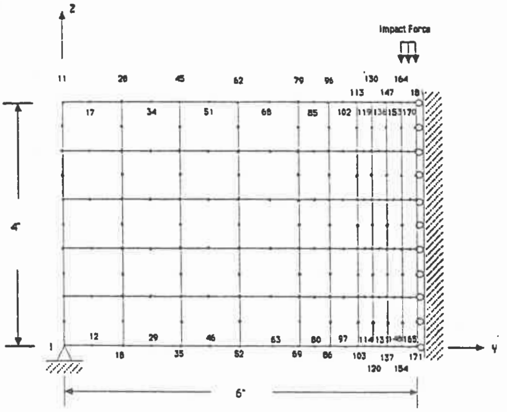

Fig. 6 Finite element mesh

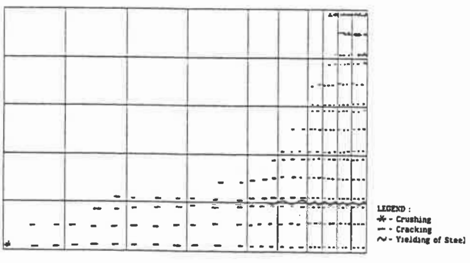

Fig. 7 Crack pattern

The solution procedure for this dynamic nonlinear analysis consisted of time-step mode superposition taking into account only the local nonlinearities. The analyses were executed using 7 modes with no damping. The first three significant modes were considered adequate.

A lumped (diagonal) mass matrix was determined for the distributed mass, and the structural and material damping were ignored. A modified Newton iteration method was used to solve the equilibrium equations.

The program also requires as input, the beam model idealization using finite elements and the load-time curve of the impact. This load-time curve was an unknown in the analysis, necessitating a trial and error method to obtain the final load-time curve necessary for failure of the beam. Using the force and stress outputs at many different locations, the program determined the crack development within the concrete. Consequently a cracking pattern was established as the failure criterion, Fig. 7.

The results obtained from the ADINA analysis are tabulated in Table 1. Typical final input load-time functions, for 2-week and 3-week corroded beams are shown in Fig. 8. The energy found in Table 1 is obtained using the relationship given by Eqn. 1, where, the integral of $p_o dt$, is the area under the load-time curves of Fig. 8, and the velocity, v, is an output parameter of the ADINA analysis.

Table 1. ADINA analysis

Beam modeling type	P_{max} (kips)	t_{max} (ms)	v_{max} (in/s)	DE_o (ft-lb)	Y_{max} (in)	Relative energy level
uncorroded	2.17	5.0	31.0	255.2	.024	1
1-week corroded	19.8	4.0	29.1	170.4	.021	0.668
2-week corroded	19.3	3.3	29.1	133.4	.021	0.523
3-week corroded	18.6	3.0	28.2	111.5	.020	0.447

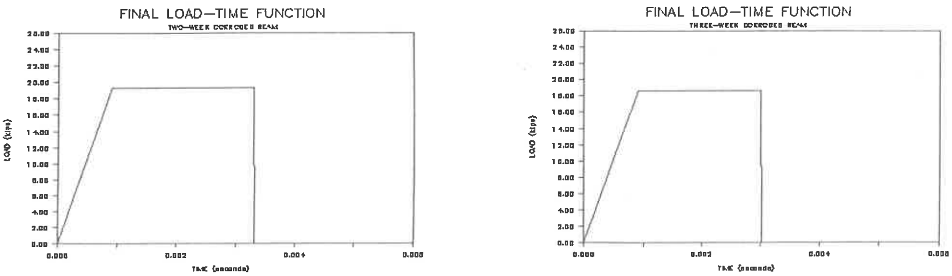

Fig. 8 Final load-time functions used in ADINA

From these results it is observed that the failure loads obtained from the four analyses do not vary very much. However, in view of the decreasing rise times, the energies absorbed by the four different beam models varied significantly

6. DISCUSSION

The results are summarized in Table 2.

Table 2. Comparison of results

Analysis	Beam modeling type	P_{max} (kips)	DE_o (ft-lb)	Y_{max} (in.)	Energy ratio $\frac{\text{n-week corroded}}{\text{1-week corroded}}$
Mathematical models	impact equation	29.7	387.3	-	
	2-D-O-F	26.6	365.4	0.012	
	3 D-O-F	16.4	364.8	0.007	
ADINA	uncorroded	21.7	255.2	.024	1.5
	1-week corroded	19.8	170.4	.021	1.0
	2-week corroded	19.3	133.4	.021	0.782
	3-week corroded	18.6	111.5	.020	0.654
Experimental investigation	uncorroded	-	-	-	
	1-week corroded	7.63	219.5	-	1.0
	2-week corroded	7.63	177.3	-	0.808
	3-week corroded	6.97	160.8	-	0.733

The energies corresponding to the three physical models, and the loads obtained from the first two of these compare favorably with each other, while the load in the three-degree-of-freedom model is approximately 60% that of the two-degree-of-freedom model. Also, the ADINA load values are considerably larger than the experimental values. Both the discrepancies are due to the inertial effects of the isolation block which is the extra mass associated with additional degrees of freedom.

More experimental investigations in combination with more accurate finite element analyses should provide a method for predicting the minimal steel cross-sectional area acceptable for ultimate load design criteria. This reduced cross-sectional area could be translated into years of seawater exposure. This would enable estimates of the life of a reinforced concrete structure in seawater subjected to impact.

7. ACKNOWLEDGEMENT

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