ANALYSIS OF A GANTRY CRANE
FOR SEVERE SEISMIC CRITERIA

by

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SYNOPSIS

This paper briefly reports on the seismic analysis and re-evaluation of a polar gantry crane subjected to criteria much more severe than the original design had dictated. Three-dimensional nonlinear analyses, incorporating rocking and cable load impact effects, were undertaken to obtain a realistic assessment of the expected behavior of the crane.

INTRODUCTION

With seismic criteria for critical facilities becoming increasingly more severe, the analysis and re-evaluation of certain classes of existing structures subjected to strong earthquake motions takes on greater importance. When it is necessary to accurately predict the expected behavior of a structure subjected to a postulated excitation considerably more severe than the originally specified design, there is often a need to resort to more sophisticated analyses than conventional problems usually dictate, including consideration of nonlinear response. The requalification of a polar gantry crane housed in the containment structure of a nuclear power plant provides such an example.

The structure consists primarily of welded steel box members and moment-resisting bolted connections. The crane, designed for a lifted capacity of 200 tons, is 70 ft (21 m) tall and 122 ft (37 m) long overall, spanning a 103 ft (31 m) diameter rail and with one end of the upper girders cantilevered beyond the legs. Transversely, the frames, 24 ft (7.3 m) apart, are connected by means of two end ties, upper cross beams, and lower sill beams containing the wheels. (See Fig. 1).

The seismic review criteria specified consideration of motion in three directions simultaneously. The amplified 7% damped response spectra at the supporting floor had zero-period values of 0.9g and 0.5g with peak values of 3.3g and 1.3g for horizontal and vertical accelerations, respectively. The objective of the analysis was to demonstrate that operating with or without load, the crane could satisfactorily resist the postulated earthquake. Because the crane travels on a circular rail, the beneficial effects of sliding could not be used to reduce seismic forces. However, realistic assessment of its structural behavior required consideration of large-amplitude nonlinear response which included rocking and impact effects. The structural stability criteria specified that the seismic loading should not produce overturning and that the seismically induced forces would not impair the structural integrity of the crane. A more complete report of the study is given in Ref. 1.

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METHOD OF ANALYSIS

Initially, response spectrum analyses of the loaded and unloaded crane were undertaken using a linear three-dimensional finite-element model. The results indicated that the uplift reactions exceeded the anchorage hold-down capacity, and thus, linear analyses were inappropriate. However, the solution did provide an upper bound to the required hold-down forces.

Following an examination of the overall crane stability using energy considerations, two-dimensional nonlinear analyses were performed to obtain an estimate of expected response and to determine the sensitivity of several important parameters, notably the gap element impact spring stiffness, solution time increment, damping, and load suspension length. The cranes were modeled as transverse and longitudinal nonlinear frame structures consisting principally of beam-column elements; nonlinear gap elements at the support points allowed the model to uplift and rock during dynamic response. It is of interest that Huckelbridge and Clough,[2] using non-linear gap elements and a method of analysis similar to that followed here, satisfactorily correlated experimental and analytical results from an investigation into the seismic response of an uplifting building frame. For the loaded case, the cable was modeled with a nonlinear truss element having zero buckling strength in order to simulate the impact effects of the cable-suspended load. Parameter studies confirmed that the critical load position would be for the minimum suspension length for which a more severe snap action prevails.

The results from the two-dimensional analyses were used to develop the model for the final three-dimensional analyses using a modified version of the ANSR-1[3] computer code. The three-dimensional nonlinear model is shown in Fig. 1. It consists of linear beam-column elements to represent the legs, girders, and end ties (semirigid at the structural member connections); a nonlinear truss element to simulate the cable; and nonlinear boundary-gap elements at the support points. Two boundary conditions were investigated. In one case, the effect of existing rail clamps between the wheel assemblies and the rail was taken into account; in the other case, it was assumed that the rail clamps were not effective. This latter condition provides a bound to the solution should the clamp or rail anchorage system fail. The condition with rail clamps was represented by an element that consisted of a compressive and tensile spring separated by a 0.5 in. (13 mm) gap. For the case without rail clamps, no tensile forces were allowed to develop. The seismic excitation consisted of the three statistically independent acceleration records generated to match the smoothed floor response spectra. Two load conditions were considered:

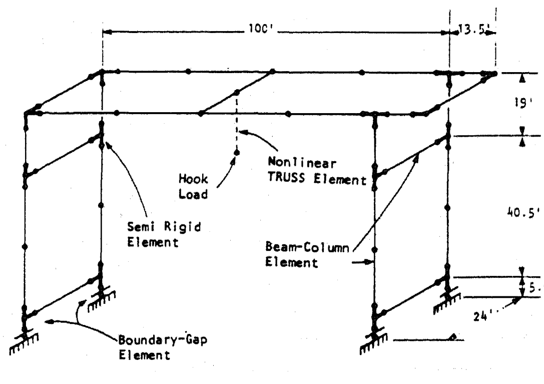

FIG. 1: THREE-DIMENSIONAL NONLINEAR MODEL

no hook load and a load of 200 tons suspended on the minimum cable length of 17.5 ft (5.3 m). The stepwise time integration of the incremental equations of motion was undertaken for a duration of 20 sec with a time step of 0.005 sec. Damping proportional to mass and tangent stiffness and equivalent to 7% of critical for the first two modes was used in the analyses.

The records of separate response effects were plotted and examined to obtain the maximum combined effect. The resulting stresses were compared with allowable values.

RESULTS

The preliminary analyses based on energy balance considerations indicated that the rocking mode of response associated with the postulated event was very stable. The energy required to cause overturning of the crane without rail clamps was almost six times the energy associated with the seismic motion. The effect of the rail clamps was to reduce the maximum uplifts to less than half those for the situation with free uplift.

Results from the more detailed three-dimensional response history nonlinear analyses confirmed that the rocking response was stable. With rail clamps, the maximum uplift was approximately 0.65 in. (17 mm). Maximum relative displacements at the top of the crane were approximately 4.5 in. (110 mm) transversely and 7.5 in. (190 mm) longitudinally. The displacements were the same for the loaded and unloaded cases. For the condition without rail clamps and unloaded, the maximum uplift was approximately 4 in. (100 mm). Maximum relative displacements at the top of the crane were 12 in. (305 mm) transversely and 7 in. (180 mm) longitudinally. For the condition without rail clamps and loaded, the maximum uplift was 3 in. (80 mm). The vertical displacement history at the base of one leg of the loaded crane is shown in Fig. 2. The crane uplifts several times with a recurrence interval of approximately 1 sec. This compares with the natural period of transverse vibration for the linear three-dimensional model of 0.55 sec. Maximum relative displacements at the girder level were approximately 10 in. (250 mm) and 7 in. (180 mm) for the transverse and longitudinal directions, respectively. Corresponding response histories are shown in Fig. 2.

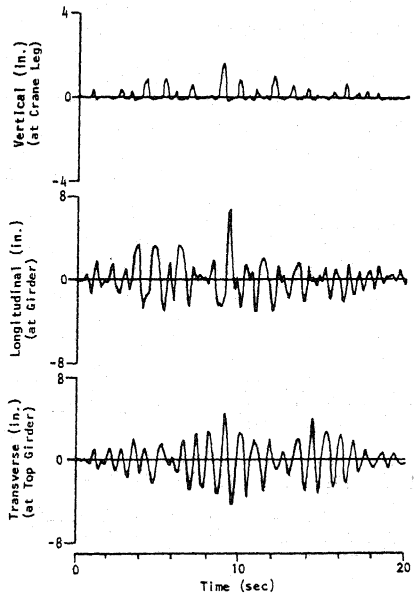

FIG. 2: DISPLACEMENT RESPONSE HISTORIES OF CRANE 200-TON LOAD - WITHOUT RAIL CLAMPS

The vertical and transverse displacement histories of the hook for the condition without rail clamps and with a load of 200 tons are given in Fig. 3. Vertical oscillations with a frequency of 2.5 Hz and a peak extension of over 3 in. (180 mm) are indicated and pendulum motion with a peak displacement of approximately 24 in. (610 mm) is apparent. The corresponding maximum cable tension was 550 tons which represents an impact effect of almost three times the static load. However, resulting cable stresses were still only 60% of allowable values.

For the condition without rail clamps, the crane was slightly less responsive (in terms of displacement) for the loaded case than the unloaded case, although the bending moments and axial forces in the structural members were slightly greater for the loaded case. Likewise, the forces on the crane members were greater for the model with rail clamps than without clamps, even though the seismic-induced displacements were less for the restrained case. This demonstrates potential benefits of unrestrained, but controlled, response under dynamic oscillatory excitation.

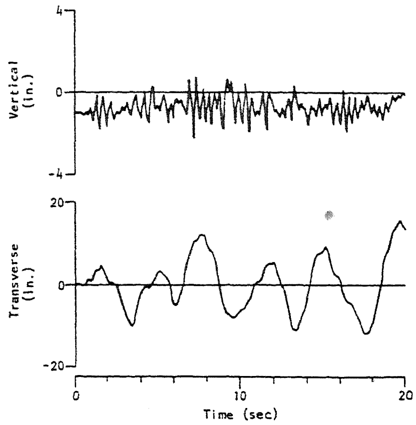

FIG. 3: DISPLACEMENT RESPONSE HISTORIES OF HOOK. 200-TON LOCAL WITHOUT RAIL CLAMPS

CONCLUSION

The results confirm the viability of undertaking nonlinear analyses of crane structures subjected to severe seismic motion. Although linear analyses indicated severe overstressing, the nonlinear analyses indicated a stable rocking mode of response would prevail and that seismically induced forces would not impair structural integrity of the crane.

ACKNOWLEDGEMENTS

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