Seismic Fatigue Evaluation of Rod Hung Systems

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ABSTRACT

Shake table tests and past earthquake experience data have demonstrated that the seismic capacity of rod hanger support systems is limited by threaded rod low cycle fatigue life. Instances of seismic damage have occurred to short, fixed-end rods, with heavy supported loads, subject to long duration motion. A procedure is presented which provides in-plant screening evaluation guidelines for these support types. The seismic capacity criteria are based on low cycle fatigue tests of threaded rods. Seismic demand is defined in terms of bounding seismic response spectra and matching time histories. Simplified linear analyses of idealized systems are used to define bounding acceptance parameters for rod hangers, considering cyclic response calculations of cumulative fatigue usage factor. A non-linear analysis study demonstrates safety margins in the developed guidelines. The developed procedure is illustrated by an example application.

INTRODUCTION

Non-seismic design rod hanger trapeze support systems for piping, cable trays, conduit, and HVAC duct have generally performed well in power plants and industrial facilities subject to past strong motion earthquakes. The good seismic performance is attributed to member and connection ductility, high anchor capacity, and inherent stability from large displacement pendulum response effects. The limited cases of rod hanger support seismic damage are from anchor failures and hanger rod low cycle fatigue failures. Observed anchor failures are due to poor installation, low capacity concrete, and undersized or poorly detailed anchors. Seismic damage to rod hanger support anchorage can be avoided by assuring high vertical design capacity and will not be discussed in detail herein; this paper's focus is low cycle fatigue evaluation.

Past earthquake performance shows that fatigue damage is limited to relatively short, fixed-end rods. Shake table tests of portions of rod hung systems show that rod hanger fragilities are governed by low cycle fatigue life of threaded rods. The tests indicate that short, fixed-end rods with heavy support loads are most vulnerable. Many component tests have been conducted, defining number of cycle limits for rod fatigue. In the following sections, an analytical approach is described and an example application is presented, which utilizes available rod fatigue test data to define acceptance parameters for rod hanger trapeze supports, with appropriate factors of safety.

SEISMIC CAPACITY

Several low cycle fatigue tests of fixed-end threaded rod hangers addressing various rod sizes, materials yield strengths, tensile pre-loads, rod connection details, and support geometries have been performed (Keowen et al, 1980, URS/Blume & Assoc., 1983 and 1984, and Stevenson & Assoc., 1987). All tests (297 specimen total) considered constant amplitude applied deflection cycled until failure, with peak ductility demands up to 8. Test result reviews conclude that correlation between equivalent strain range and logarithm of number of cycles until failure provides good representation of the test data. Equivalent strain range is illustrated in Figure 1 and defined by simple beam theory as follows:

$$\epsilon_R = \frac{6R}{L^2} \; (2\Delta\ )$$

Equivalent strain range versus log of number of cycles to failure for the reference rod hanger fatigue tests are shown in Figure 2, with mean less two standard deviation best-fit regression analysis line. All tests fall above the lower line capacity criteria except for field threaded rod data. Field threading evidently effects fatigue life: acceptable strain ranges are only about 70% of those for manufacturer threaded rods.

SEISMIC DEMAND

Seismic demand definition for fatigue evaluation includes response spectrum, duration, and damping. For an example fatigue evaluation, the broad band bounding spectrum of Figure 3 is considered, with 30 second duration time history. The example considers 5% damping for lower frequency raceway systems, with long continuous runs, responding in a lateral swaying mode. The bounding spectrum arbitrarily matches a RG 1.60 spectrum (AEC, 1973) in the low frequency range, and the SSRAP bounding spectrum (SSRAP, 1987) at higher frequencies.

FATIGUE ANALYSIS

The capacity criteria define acceptable number of cycles to failure for imposed strain ranges. For a trapeze with fixed-end rod connection details, strain range is a function of imposed displacement, rod diameter, and rod length. The number of cycles to failure is a function of response frequency, assuming linear response. Imposed displacement is also a function of response frequency, assuming linear response. With these functional relations, the key variables are rod diameter, length, and response frequency. For a given rod diameter, it is possible to solve for a critical fatigue length at each response frequency.

A set of seismic demand displacement response time histories are generated, using the bounding spectrum seismic demand time history as input motion, for single degree of freedom oscillators. Sixty response frequencies from 0.25 to 10 Hertz are used. For each rod diameter size, an iterative solution is carried out to determine critical rod length for each frequency dependent seismic response displacement time history. A starting rod length is selected, then subject to the displacement response time history. For each half cycle of imposed displacement, rod strain range is calculated and fatigue usage factor is determined by comparison with the capacity criterion for that strain range. Cumulative usage factor calculations are by the Palmgren-Miner rule. For a given rod diameter, response frequency, and bounding response spectrum, critical fatigue rod length is obtained when cumulative usage factor equals 1.0.

Half cycles of imposed ductility demand are identified by the rain-flow cycle counting algorithm (Wirshing and Shehata, 1977). This method accounts for all strain ranges of the response time history. The rain-flow method identifies strain ranges compatible with constant-amplitude fatigue data, identifying strain half-cycles associated with closed hysteresis loops. The method simulates rain flowing down a roof (time history oriented vertically). Each flow path is considered a half-cycle, with a strain range equal to the difference between the maximum and minimum strains of the flow path.

The results of the iterative solution provide criteria for minimum acceptable rod lengths at each response frequency. Example results for a 5/8 inch diameter rod (manufacturer threaded) and the 0.50g bounding spectrum are shown in Figure 4. The figure shows that supports with lower response frequencies require longer minimum acceptable rod lengths.

SCREENING CHARTS

Single degree of freedom approximations are used to convert the minimum acceptable rod length versus response frequency criteria into a format for in-plant screening charts. For the example long, continuous raceway run with uniform (constant rod length) supports are considered. Peak displacement response is estimated as decoupled response of a single support with mass corresponding to tributary span dead weight. Using simple beam theory and including an adjustment for pendulum response, frequency is estimated as:

$$f = \frac{1}{2\pi} \left[\frac{2(12EI/L^3) + (W/L)}{(W/g)} \right]^{1/2}$$

With this approximation, frequency (f) is only a function of rod length (L) and support dead weight (W) for a given rod size. Setting f and L to each acceptable rod length and response frequency combination, W is solved for. Results are shown in Figure 5, which presents the fatigue solutions of Figure 4 as simple combinations of L and W. Superimposed on Figure 5 is a broadened envelope for in-plant screening, providing criteria of minimum acceptable rod lengths for maximum acceptable support dead weights.

The basis for the screening envelop is as follows. Line A-B screens out configurations with response frequencies higher than the worst-case at point "B". This prohibits acceptance of configurations where nonlinear effects may shift response to lower, more governing frequencies. Line B-C provides a close fit to the raw analytical results on the low frequency side. For raceway systems, low response estimation by decoupled model approximations are offset by damping increases with raceway stiffness contribution. Corrections for line B-C may be warranted for lower damping systems such as piping. Line C-D on Figure 5 clips fatigue analysis results by the rod axial prestress limits used in the fatigue tests (mean stress is a second order effect for fatigue life). Extension of line C-D beyond the critical fatigue zone also sets a dead load factor of safety for in-plant screening. Line C-D may be set at lower values as governed by anchor capacity safety factors.

VALIDATION STUDY

The fatigue evaluations are based entirely on linear-elastic analyses. A non-linear analysis is conducted to assess margin, considering elastic-perfectly plastic hinge formation at rod connection points, and large displacement effects. The non-linear model configuration corresponds to the governing point "B" of Figure 5. Figure 6 compares linear-elastic and nonlinear time history analyses. The dampening effect of the hanger's hysteritic behavior is illustrated. For the non-linear case, fatigue calculations predict a usage factor of only 0.46, indicating a safety margin of 2.2 over the linear-elastic case. This margin more than compensates for any unconservatisms associated with the simplified calculational process.

CONCLUSION

The presented methodology provides simple and conservative screening seismic evaluation criteria for acceptance of rod hung systems. The developed criteria focus on rod hanger fatigue life, which earthquake experience and shake table tests have shown to govern fragility. The developed screening charts can be adapted to also address anchorage capacity.

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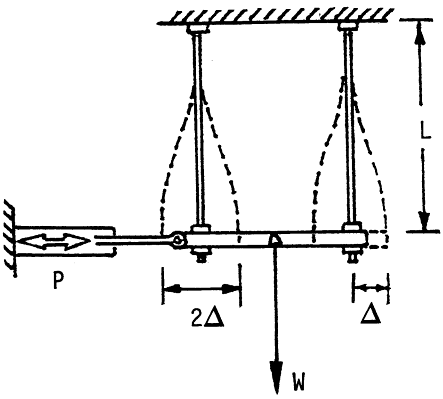

Figure 1: Fatigue strain range corresponds to a double test deflection amplitude.

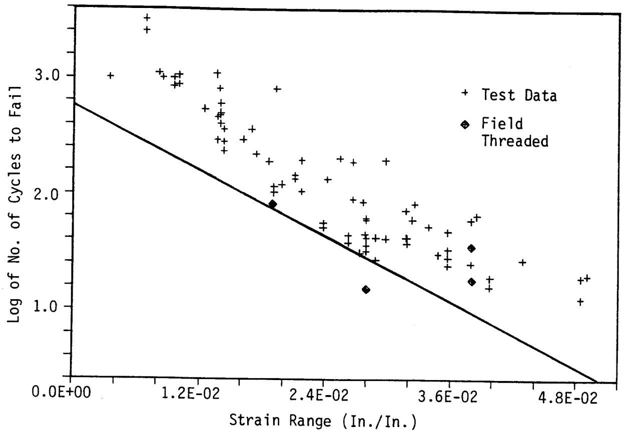

Figure 2: Rod fatigue test data, with mean less two standard deviation capacity criteria.

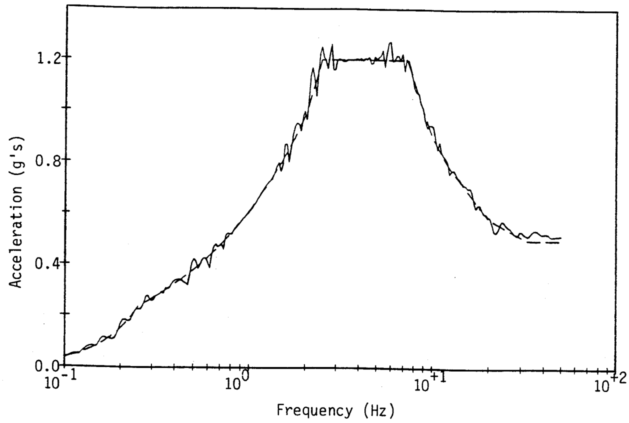

Figure 3: 0.50g bounding rod fatigue spectrum and matching time history spectrum.

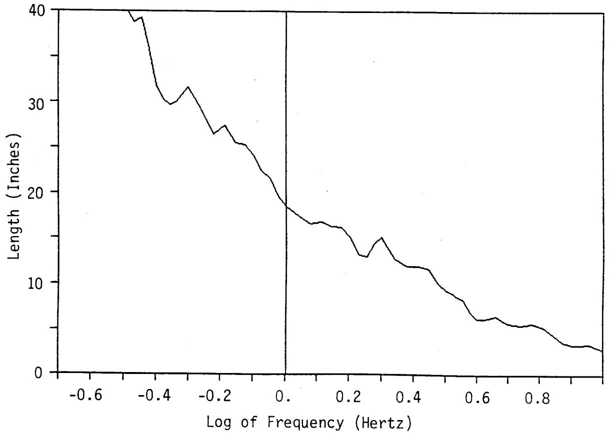

Figure 4: Response frequency versus critical rod fatigue length (minimum acceptable length).