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Automated Measurement of Stress in Continuous Welded Rail

SUMMARY

Most modern railways use continuous welded rail (CWR). A major problem in CWR is the almost total absence of expansion joints to accommodate seasonal thermal changes. This lack of joints results in derailments because of so-called sun kinks or buckling in hot weather (Figure 1) and breakage or pull-apart in cold weather. A related critical parameter is the rail neutral temperature (NT), or the temperature at which there is no longitudinal tensile or compressive stresses. To ensure safety of operation in CWR, reliable information on the level of stress in the rail is critical. Unfortunately, the currently available methods for stress measurement in CWR suffer from unacceptable drawbacks of inefficiency and/or unreliability. The static rail stiffness measurement method requires unfastening a long segment of rail. The D'stresen technique involves fastening/support condition variation challenges. And, the acousto-elastic technique's drawback is low sensitivity to stress levels.

In June 2008 the University of California, San Diego (UCSD), under the sponsorship of a Federal Railroad Administration Office of Research and Development grant, began work to develop a technique for stress measurement in CWR, which can give reliable data without the above noted drawbacks. Task 1 (completed) was aimed at performing numerical wave propagation analyses in loaded rails. These analyses identified several features of ultrasonic guided waves, which are indeed sensitive to load levels in the rail with minimal influence of the rail supports. In Task 2 (ongoing), a proof-of-concept test was conducted on a steel I-beam subjected to varying levels of compression load up to incipient buckling. The ultrasonic wave features sensitive to load levels were confirmed in this test. Also in Task 2, a large-scale full rail track (70 feet in length) has been constructed at UCSD's Powell Structural Laboratories, among the largest laboratories in the country for structural testing. This track, with in-kind materials donations by Burlington Northern Santa Fe, will stay in place for at least 1 year to conduct a series of experiments involving heating cycles through NT and buckling conditions. During these experiments, several dynamic measurements will be taken to validate the ultrasonic features identified previously as good candidates for NT and incipient buckling detection. The results of the large-scale tests are expected to lead to the development of a prototype for NT/incipient buckling detection that can be used either in motion or in a stationary manner.

Figure 1. Buckling in a CWR

BACKGROUND

Knowledge of stress levels or neutral temperature (NT) in continuous welded rail (CWR) is critical to avoid breakage in cold weather and buckling in hot weather. According to Federal Railroad Administration (FRA) Safety Statistics Data, rail buckling was responsible for 48 derailments and nearly $30 million in direct cost during 2006 alone in the United States. Methods under consideration for the measurement of applied stress (or NT) in rail today include:

1. **Measurement of static rail stiffness**. Although effective, this approach is cumbersome and not practical because it requires unfastening of ~100 feet (ft) of rail.
2. **Measurement of dynamic resonance of torsional mode of vibration (D'stresen method)**. The D'stresen technique is based on the measurement of dynamic resonance (acceleration amplitude) below 90 hertz (Hz) for the torsional mode of vibration of the rail. D'stresen does not require unfastening, hence the potential attractiveness. Unfortunately, D'stresen is highly sensitive to rail fastening/support conditions. Hence normal tie-to-tie variations can make the stress or NT measurement unreliable with this method.
3. **Measurement of ultrasonic velocity (Acousto-Elastic method)**. Acousto-elastic stress measurement typically uses longitudinal, shear or surface (Rayleigh) waves in the ~MHz frequency range. Unfortunately, the acousto-elastic variation of wave velocity with stress is extremely small (~0.1 percent velocity change per gigapascal of stress), such that the stress indications are often masked by other factors (temperature variations and steel microstructure variations).

The railroad industry would benefit from a noninvasive technique for measuring stress in rails while in motion and with a sensitivity large enough to overcome the effects of changing tie-to-tie conditions, temperature, or microstructure.

The midfrequency dynamic range is particularly attractive because of its reduced sensitivity to the rail supports (fasteners, ties, and ballast).

Through a research grant to the University of California, San Diego (UCSD), a project was started in June 2008 to ultimately develop a system able to determine the rail NT and condition of incipient buckling in CWR. The current Task 2 was aimed at (1) completing the numerical analyses, (2) performing a proof-of-concept buckling test on a steel I-beam, and (3) constructing a large-scale track testbed for controlled heating and buckling experiments at UCSD's Powell Structural Laboratories.

NUMERICAL ANALYSES

The Semianalytical Finite Element (SAFE) method was used to simulate the behavior of ultrasonic guided waves in loaded rail. SAFE requires only the discretization of the cross-section of the rail to predict both forced and unforced wave solutions (Figure 2).

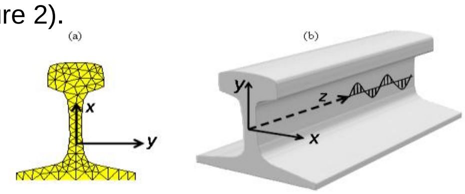

Figure 2. SAFE Model of Wave Propagation in Rails: (a) Cross-Sectional Discretization; (b) Harmonic Motion along Propagation Direction

With the algorithms developed by Bartoli et al. [1] and Loveday [2], it was possible to simulate changes in the velocity of specific guided wave modes as a function of load applied to the rail. Figure 3 shows the phase velocity dispersion curves for three dominant vibrational midfrequency wave modes for the case of unloaded rail and loaded rail (0.1 percent tensile strain). Appreciable changes in wave velocity between the unloaded and the loaded rail can be observed for the flexural vertical, the flexural horizontal, and the torsional wave modes. It should be noted that this change in velocity is much higher than that obtained by the conventional Acousto-Elastic method, which uses ~MHz wave frequencies.

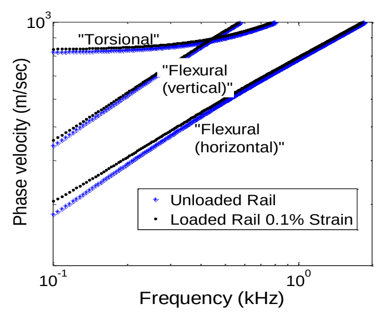

Figure 3. Changes in Phase Velocity of Three Dominant Vibrational Midfrequency Wave Modes for the Case of Unloaded Rail and Rail Loaded Axially at 0.1 Percent Tensile Strain

Figure 4 shows the mode shapes of the two fundamental flexural modes. As expected, the flexural horizontal mode has large lateral displacement components, whereas the flexural vertical mode has a prevalent vertical motion.

The torsional mode is another guided mode with propagation velocity influenced by the applied axial load.

The data provided by these analyses are the first steps to developing a prototype able to detect stress levels in CWR based on information gathered from selected wave modes.

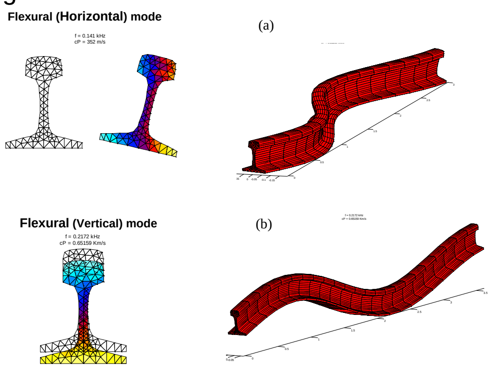

Figure 4. (a) Flexural Horizontal Wave Mode and (b) Flexural Vertical Wave Mode

PROOF-OF-CONCEPT LOAD TEST OF STEEL I-BEAM

A proof-of-concept test was conducted on a 2-meter-long, S3×5.7 steel I-beam that was subjected to increasing levels of compression loads up to incipient buckling (Figure 5). Ultrasonic guided wave measurements were taken at each load level through an array of piezoelectric transducers installed on the beam flange.

A specific feature of the guided waves was identified as particularly sensitive to the load levels. This feature is plotted in Figure 5 as a function of the load applied to the beam. It can be seen that this feature follows well the level of load in the beam and is also clearly sensitive to conditions of incipient buckling.

If this behavior is confirmed on a rail geometry, this feature will be an ideal candidate for an NT/incipient buckling detection system.

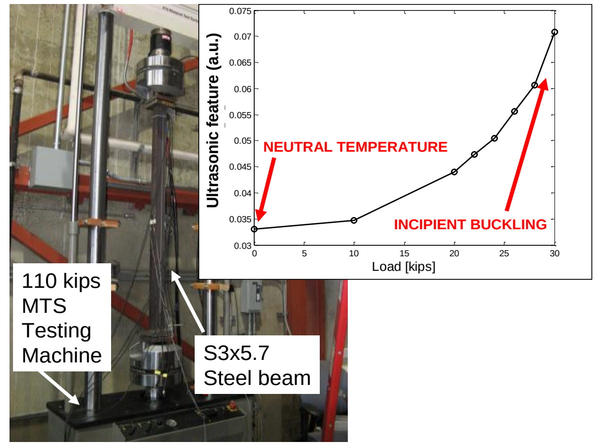

Figure 5. Compression Test on a Steel I-Beam with Plot of Ultrasonic Feature Sensitive to Load Levels and to Incipient Buckling.

LARGE-SCALE TRACK TESTBED AT UCSD's POWELL STRUCTURAL LABORATORIES

In an effort to confirm the results of the previous phases on a real CWR rail track, a unique testbed has been constructed at the Powell Structural Laboratories. The testbed features a 70-foot-long full track that has been pretensioned and held in place by a posttensioned concrete block at each end. Materials for the testbed were donated in part by the Burlington Northern Santa Fe (BNSF) railway. This track will be subjected to a series of heating tests through a specially designed rail switch heater wire. In addition, the track will be buckled with the aid of hydraulic actuators. During these tests, the full static and dynamic behavior of the track will be recorded by arrays of strain gages, linear variable differential transducers, accelerometers, and ultrasonic transducers. It is planned to record the full dynamic behavior of the track, including the low frequencies (~100s Hz) and the high frequencies (~MHz).

The testbed will stay in place for at least 1 year to enable acquiring these measurements during multiple heating cycles. In coordination with UCSD and FRA, the testbed will also be available to other researchers interested in the topic of NT and buckling of CWR.

These tests are expected to reveal specific dynamic/wave features of the rail to use in an NT/incipient buckling detection system. The main requirements for such features will include (1) high sensitivity to load levels and (2) low sensitivity to the rail supports or tie-to-tie variations.

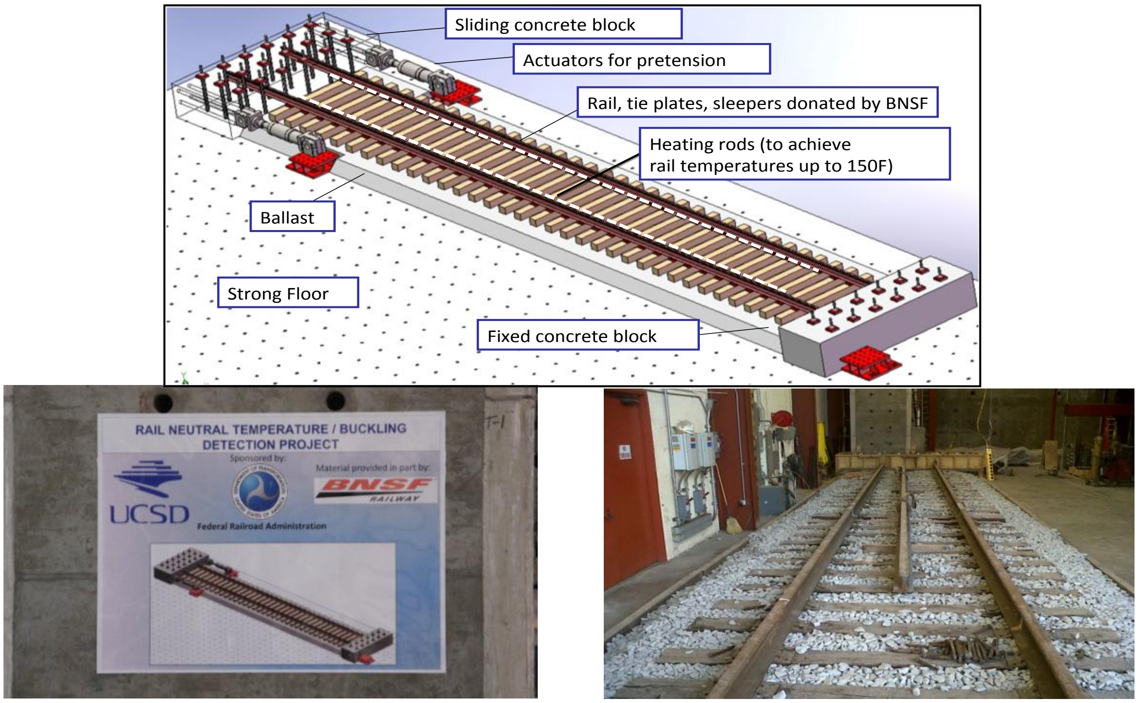

Figure 6. The Large-Scale Track Testbed at UCSD's Powell Structural Laboratories for the Development of an NT/Buckling Detection System for CWR

CONCLUSIONS

UCSD is developing a system able to measure NT and detect conditions of incipient buckling in CWR. The system will use specific ultrasonic wave features with little sensitivity to the rail supports. A unique large-scale track testbed, 70 ft in length, has been constructed at the Powell Structural Laboratories for studying the dynamics of CWR under thermal cycles and at buckling.

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REFERENCES

[1] Bartoli, I., Marzani, A., Lanza di Scalea, F., & Viola, E. (2006). Modeling wave propagation in damped waveguides of arbitrary cross-section. *Journal of Sound and Vibration*, *295*, 685-707.

[2] Loveday, P.W. (2009). Semi-analytical finite element analysis of elastic waveguides subjected to axial loads. *Ultrasonics*, *49*, 298-300.

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