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BENEFICIAL RESIDUAL STRESSES AT BOLT HOLES BY COLD EXPANSION

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ABSTRACT

Cracking at rail-end-bolt holes is a major safety issue and cause of premature rail replacement, imposition of rail speed restrictions and a significant factor in rail inspection and maintenance costs. The presence of residual compressive stresses around these bolt holes has been shown through exhaustive testing and field evaluation to minimize fatigue cracking and thereby extend inspection intervals and allow for higher axle loads. Split sleeve cold expansion is an economical and reliable method to pre-stress bolt holes during routine track maintenance or manufacture of new rail, joints and switches.

This paper reviews the evaluation of methods to overcome bolt hole fatigue failure. It describes the split sleeve cold expansion technique in detail and the mechanism by which these beneficial residual stresses effectively nullify fatigue causing cyclic tension loads and virtually eliminate the rail-end-bolt hole cracking problem.

Introduction

The problem of rail bolt hole cracking is not unique to any specific railroad, region or country but is recognized as a worldwide problem. Railroad tracks are continually subjected to high loads generated by the passage of rolling stock. Flexing and displacement of rails at bolted joints combine to induce high cyclic tensile and shear loads in the joint bar, or fish plate, which are transferred to the attaching bolt holes. Numerous studies and reports (see for instance [1] and [2]) detail research conducted to define the problem of rail-end-bolt hole cracking and to address practical solutions designed to minimize or prevent rail joint bolt hole failure. As shown in Figure 1, the most dangerous situation arises in jointed track when cracks occur at a bolt hole because fracture usually results in a piece of rail becoming detached.

In 1974, the U.S. National Transportation Safety Board (NTSB) identified broken rails as the largest single cause of train accidents [3]. Between 1982 and 1988, track-caused-accidents represented between 30 and 40 percent of the total number of the reported accidents [4] and total incurred costs of recovery. Specifically, Federal Railroad Administration statistics for 1988 [5] showed bolt-hole-caused derailments accounted for a high cost per accident and a significant 10 percent ($2,136,221) of the total cost of rail and joint bar defects.

Figure 1 Typical Bolted Rail Joint

Similar statistics have been recorded in the U.K. In the early 1980's, over 3000 cracked and broken rails of different types were reported each year, with the highest number of incidents occurring on middle-speed range, heavily loaded track. Of these, about 25 percent were caused by cracks originating at rail-end-bolt holes. Between 60 and 70 percent were detected while still in the cracked stage before actual fracture.

More recently, tests were carried out as part of the Heavy Axle Load (HAL) Program for the U.S. rail industry [6] to investigate the effect of increased axle loads and speeds on existing track. It was found that an increase in axle load of only about 20 percent precipitated serious cracking in bolt holes in turnout frogs and switches.

Loading of the rail web and additional localized loads significantly increase the magnitude of the applied stress acting on a typical bolted joint when axle loads and speeds are increased. These loads are further magnified by dynamic effects in turnouts and curves or where the rail bed fails to adequately support the rail tie or sleepers.

Mechanism of Joint Failure

Cracks originating from rail joint bolt holes are the result of web shear stresses. In the U.S. Department of Transportation report [2] it was concluded that these stresses develop in the rail end when the joint bar transmits the bending moment across the joint through concentrated point contact at the rail and the end of the joint bar (Figure 2). This condition occurs whenever the joint bar becomes loose or, on installation, was not nested correctly between the head and flange of the rail. British Railways, in their studies on the effect of track and vehicle parameters on wheel/rail vertical dynamic forces [7], concluded the cause of bolt hole cracking is shear stress associated with dynamic wheel/rail forces generated by a dynamic dip at the joint.

The shear stress in the rail web is then magnified by the stress concentration effect of the bolt hole and other surface defects such as corrosion pits and material imperfections that may be present. Additional dynamic loads on the rail joint, including those due to loose bolts and collapsed rail bed, add to the hoop surface stress of the hole. Two cracks generally initiate, one growing towards the rail head and the other one towards the base of the rail. They propagate along a 45 degree plane, as shown in Figure 3. If cracks are not detected before they become critical, usually 5-10 mm long, fracture can occur, often dislodging a triangular piece of rail which can lead to derailment.

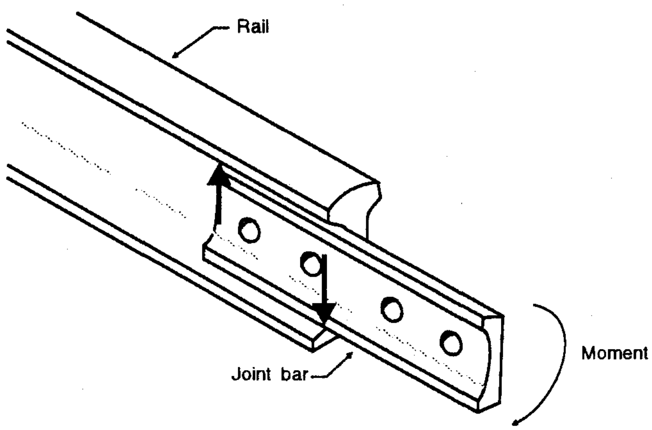

Figure 2 Loads Applied to a Typical Bolted Rail Joint [2]

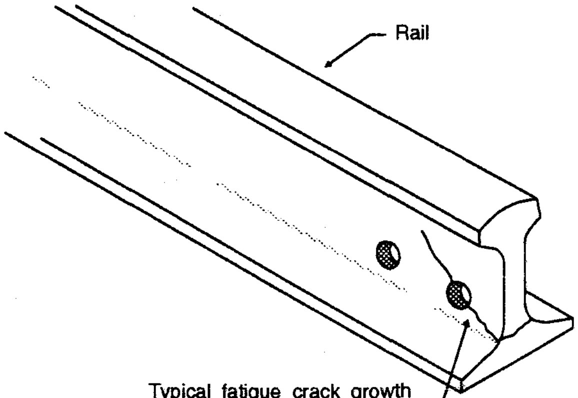

Figure 3 Typical Cracks Originating at Rail-End Bolt Hole

Fatigue Life Improvement of Rail Joints

Over the past three decades, a number of attempts have been made to mitigate the rail-end-bolt hole cracking problem. In the 1960's, British Rail increased rail-web thickness in the hope that it would proportionally reduce the high stresses and thus reduce the incidence of bolt hole cracking. About the same time, a hole "broaching" process was tried in laboratories to "work harden" the hole surface and locally increase its fatigue strength; however, the process was difficult to control and eventually proved to be ineffective.

Some of the options that are currently available to minimize the occurrence of rail-end-bolt hole failures include: (1) replacement with continuous welded rail, although some joints may still remain; (2) increased inspection frequency, which will not prevent fatigue crack initiation; (3) reducing the usage or loading on the track, which will minimize the stress cycles at the bolt hole and therefore the failure probability, but carries an economic penalty; and (4) modify the bolt hole locally by for example, introducing compressive residual stresses to inhibit crack propagation from it. The latter approach is highly cost effective and reliable under most circumstances.

The technique of mechanically pre-stressing holes to induce favorable compressive residual stresses is successfully used by other industries, notably aerospace. Methods such as shot peening and blasting, coining, ballizing, roller burnishing, and mandrelizing, have all been evaluated. Of these, mandrelizing, i.e., the effect of forcing a tapered or multi-flanged expansion mandrel through a hole, initially appeared to show the most potential. This method results in the material around the hole being plastically deformed. However, the amount of circumferential and radial expansion of the hole is very much dependent on hole quality. Careful lubrication of the hole is also necessary to avoid material being pushed through the hole rather than being radially expanded. In its application to bolted rails, one additional requirement is the capability to reliably and repeatedly carry out the process in the field under adverse environmental conditions. For these reasons, in practice, the mandrelizing process has not performed satisfactorily.

In 1975, the U.S. Department of Transportation (DOT) sponsored a study [2] to investigate the split sleeve cold expansion process and a pad-coining method as an alternate means of pre-stressing bolt holes. The rail web thickness and unevenness in the web surface reduced the effectiveness of the pad coining process. Also, the need for coining forces exceeding 100,000 pounds (445,000 N), precluded use of this method with conventional equipment. On the other hand, in laboratory studies and later, field trials, the split sleeve cold expansion process showed significant fatigue life improvement over non-cold expanded bolt holes. Results from the DOT study are shown in Figure 4.

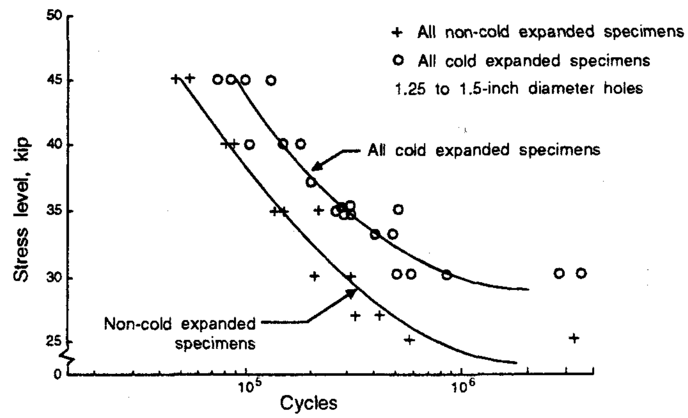

Figure 4 Increase In Fatigue Life For Cold Expanded Holes Vs. Non-Cold Expanded [2]

The results of additional extensive British Rail trial and evaluation of the split sleeve cold expansion process, including theoretical modeling and laboratory and in-service tests, is documented in [1]. Both the aforementioned U.S. Department of Transportation program and the British Rail Board trials have confirmed that split sleeve cold expanded rail-end bolt holes could increase the life of a bolted rail joint by a factor of 10 or more by reducing or eliminating bolt hole fatigue failure.

The Split Sleeve Cold Expansion Process

The split sleeve cold expansion process previously described is accomplished by pulling an oversize tapered mandrel, pre-fitted with a dry-film lubricated split sleeve, through the bolt hole using a specially designed hydraulic puller, as shown in Figure 5.

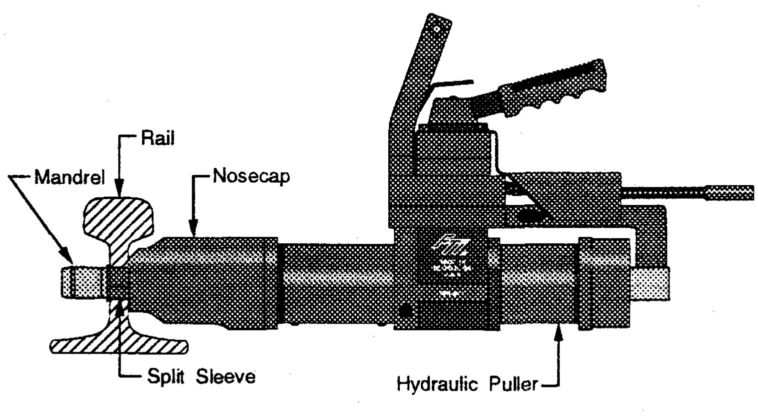

Figure 5 Schematic Of Split Sleeve Cold Expansion Process

The disposable lubricated sleeve is crucial to the process, because it reduces the pull force required and prevents local shearing of rail material as the mandrel is pulled through the hole. The combination of mandrel diameter and sleeve thickness creates very high radial pressure on the hole, and expands the hole to well beyond the yield strain of the rail steel. After the mandrel passes through the hole, the area surrounding the hole remains residually stressed in compression to a distance roughly equal to the hole radius (Figure 6). The magnitude of the peak compressive stress approaches the material compressive yield stress. This pre-stress effectively shields the hole from crack growth by counteracting the stresses imposed by the applied service loads.

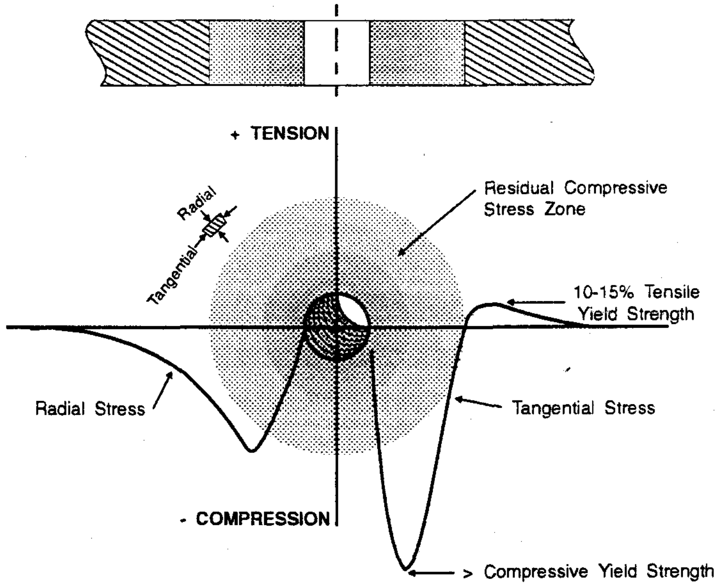

Figure 6 Distribution Of Residual Stress Around A Split Sleeve Cold Expanded Hole

Fatigue Technology, Inc. (FTI) of Seattle, Washington, USA has developed the RailTec™ Cold Expansion system of tooling to facilitate cold expansion of bolt holes in existing track or in new production rail. In a typical field application as used by British Rail, each fish-plated joint is dismantled, followed by cleaning of bolt holes and adjacent areas with scrapers and cloths. Holes are measured and cleaned up with a bridge reamer to a nominal size and then each hole is cold expanded using RailTec tooling as shown in Figure 7. Finally, the joint is re-assembled. All operations proceed simultaneously, and a production rate of about 10 joints per hour is readily achievable.

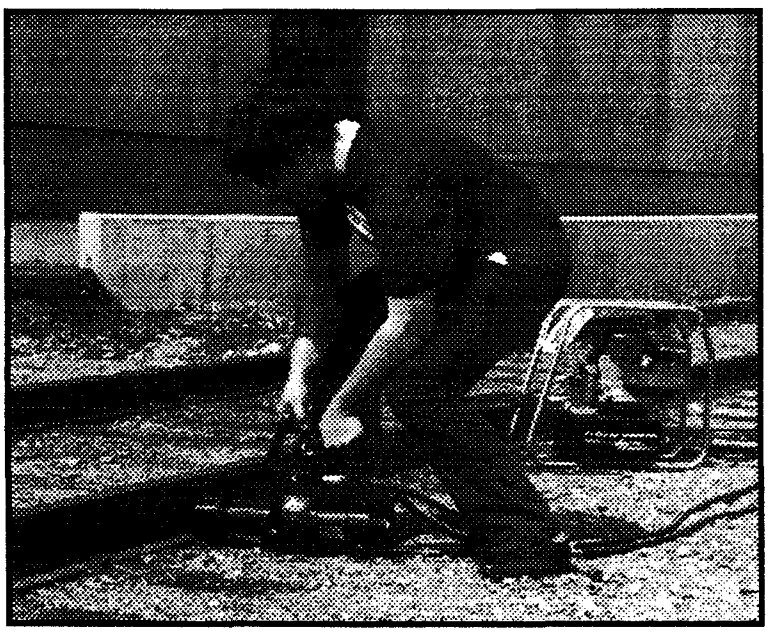

Figure 7 RailTec System In Use On Existing Track

The estimated total cost of servicing the joints during routine maintenance, including cold expansion of all holes, is about $3,000/km. This compares to the cost of converting jointed track to Continuous Welded Rail (CWR) at around $180,000/km [8], which can be prohibitively high for relatively low-revenue earning lines, and requires the track to be out of service for a much longer period of time.

Following its participation in the U.S. evaluation program, Union Pacific Railroad implemented the split sleeve cold expansion process on all new rail, switches and crossings.

British Rail also currently has a number of specialist field teams in all of its regions implementing this process. Surveys of the British Rail Western region since the RailTec system was introduced a few years ago, show a virtual elimination of occurrences of fatigue cracking from these holes. Results for the Plymouth to Penzance route (21 km), and Exeter to Sherbourne route (38 km) are shown in Figures 8 and 9 respectively [9]. Considering that some of these existing rail joint holes may have contained small or undetected cracks at the time of cold expansion, the outstanding benefits of this process are clearly evident.

Date	Star Cracks	Miles Cold Expanded	Total Miles Cold Expanded
1988	2	0	0
1989	22	1.58	1.58
1990	28	7.68	9.26
1991	7	3.83	13.09

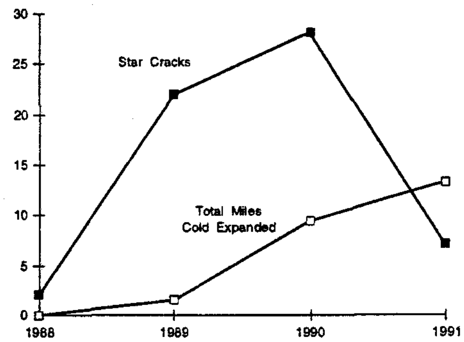

Figure 8 Survey Of Results After Cold Expansion / British Rail Plymouth To Penzance Route

Date	Star Cracks	Miles Cold Expanded	Total Miles Cold Expanded
1987	21	0	0
1988	24	8.51	8.51
1989	12	11.35	19.86
1990	6	3.64	23.5
1991	1		

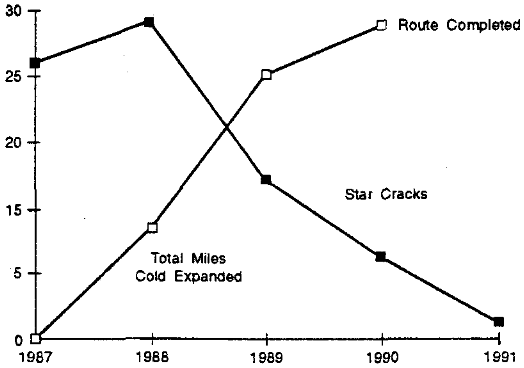

Figure 9 Survey Of Results After Cold Expansion / British Rail Exeter To Sherbourne Route

Mechanics of Cold Expansion

During the split sleeve cold expansion process, the mandrel and sleeve combination radially expands the hole beyond the yield point of the rail steel, by a prescribed amount. Plastic deformation progresses outwardly from the hole. Following travel of the mandrel through the hole, the bulk of the material, which lies beyond the plastic zone, is still in an elastic state and attempts to force the permanently deformed material in the periphery of the hole to return to its original position. The resulting effect is the creation of a band of material around the hole in a residual compressive circumferential stress state, as shown previously in Figure 6.

Residual stresses are self-equilibrating stresses existing in a material under uniform temperature conditions without external loading. In a cold expanded hole, this means that the resultant forces over a radial element produced by the cold expansion residual stresses, must be zero. This explains the small amount of residual tension away from the hole. Figure 10 shows the residual strain pattern created by cold expansion obtained by means of a photoelastic coating.

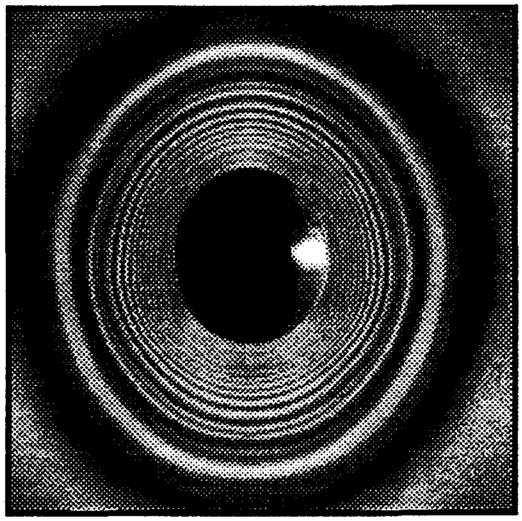

Figure 10 Residual Strain Pattern Around Cold Expanded Hole Seen As Photoelastic Fringes

For typical rail steels, the hole needs to be expanded at least 2.3 percent of its diameter to ensure adequate local yielding of the steel adjacent to the hole. When the rail-end-bolt holes incorporating these residual stresses are externally loaded by the passing of rolling stock, the effective stress state will be roughly the algebraic sum of the applied stresses and the residual stresses. With the magnitude of the residual compressive stress adjacent to the edge of the hole approximately equal to the compressive yield stress of the rail steel, the net effect of the combined stresses under in-service loads is to move the mean stress towards or into compression. This reduced net stress retards crack initiation and inhibits crack growth.

An important consideration is that cold expansion of the hole alone may not prevent (although it may retard) crack initiation. The possible presence of machining defects created during drilling or reaming, the existence of corrosion pits, and metallurgical characteristics of the material, all significantly influence crack initiation. The primary effect of the cold expansion residual stresses is to reduce crack growth rates by reducing the stress intensity factor range (ΔK) for existing cracks, as shown in Figure 11. Similar arrest of crack growth due to stress intensity reduction and distribution of "K" was reported by British Rail [1] in their research. Additionally, the presence of residual stresses may change the critical crack length for unstable fracture. The lower crack growth rates and greater critical crack lengths can be used to extend non-destructive inspection intervals for rail joints, and/or simplify inspection procedures.

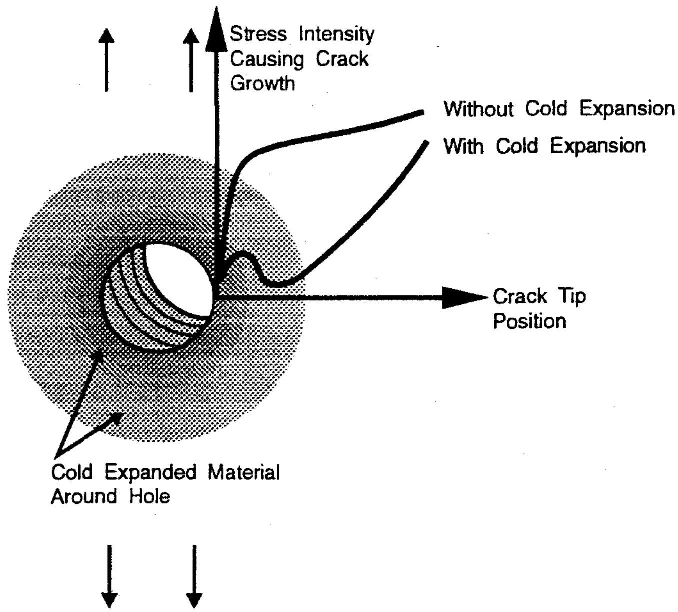

Figure 11 Reduction In Stress Intensity Factor Range (ΔK) Under Residual Compressive Stress From [10]

In a number of fatigue tests conducted by Fatigue Technology and other companies on typical aerospace materials, small pre-existing cracks were totally arrested after inducing compressive residual stresses by split sleeve cold expansion. Only a large increase in external load caused further crack growth.

Analytical modeling methods are available to predict the effect of cold expanded holes on fatigue crack growth [10, 11]. These models, and results from field implementation of the split sleeve cold expansion system confirm that the introduction of beneficial residual compressive stresses around rail-end bolt holes can delay the onset of crack initiation and slow down or totally arrest crack growth.

Conclusions:

The problem of rail-end-bolt hole cracking has been overcome by introduction of residual compressive stresses around the hole. These residual stresses lower the magnitude of the applied stresses acting near the hole, which in turn inhibits crack growth. The most cost effective method for inducing these residual compressive stresses on existing track in the field, and in production of new or replacement bolted track, switches and crossings, is split sleeve cold expansion.

The results of British Rail field surveys and observations from other users of the process confirm split sleeve cold expansion of rail-end bolt holes can be a viable economic alternative to replacement of existing bolted track. The overall result is a greatly extended fatigue life of bolted track, safer and more economical rail operation, reduced routine or special joint maintenance costs, and extended joint inspection intervals.

References:

[1] Cannon, D.F., Sinclair, J., and Sharp, K.A., "Improving the Fatigue Performance of Bolt Holes in Railway Rails by Cold Expansion." Presented at: Fatigue Corrosion Cracking, Fracture Mechanics and Failure Analysis, International Conference and Exposition, December 1985, Salt Lake City, Utah USA.

[2] Lindh, D.V., Taylor, R.D., and Rose, D.M., "Sleeve Expansion of Bolt Holes in Railroad Rail," U.S. Department of Transportation, Final Report, December 1977.

[3] Broken Rails: A Major Cause of Train Accidents, U.S. Department of Transportation NTSB RSS-74-1, January 1974.

[4] Zarembski, A.M., "Track Caused Derailments," RT&S, October 1990.

[5] "Accident/Incident Bulletin, Calendar Year 1988," U.S. Department of Transportation, Federal Railroad Administration, Office of Safety, Bulletin No. 157, June 1989.

[6] Read, D.M., "Fast/HAL Turnout Performance Experiment," American Railway Engineering Association; Bulletin No. 728 Vol. 91 (1990)

[7] Jenkins, H.H., et al, "The Effect of Track and Vehicle Parameters on Wheel/Rail Vertical Dynamic Forces", Railway Engineering Journal (IMechE), January 1974.

[8] Tolley, K.H., "Extending Track Life with Improved Safety at Reduced Maintenance Costs," International Railway Congress Association Intersessional Seminar; Budapest, May 23-24, 1991.

[9] Survey of Results from British Rail Western Region provided by British Rail Research, Derby

[10] Clark, G., "Modeling Residual Stresses and Fatigue Crack Growth at Cold Expanded Fastener Holes" Fatigue Fracture of Engineering Materials Structures. Vol. 14, No. 5.

[11] Rufin, Antonio C., "Extending the Fatigue Life of Aircraft Engine Components by Hole Cold Expansion Technology", ASME Paper 92-GT-77, presentedat the 1992 Gas Turbine and Aeroengine Congress and Exhibition, Cologne, Germany