Effects of Wear and Service Conditions on Residual Stresses in Commuter Car Wheels

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Summary: This paper illustrates application of the shakedown residual stress estimation technique to assess the effects of service conditions on wheel residual stresses. The examples described provide the technical details on how the technique is practically applied and typical results. Operational conditions representative of a commuter railroad have been used in the simulations. Results are presented for a baseline commuter vehicle illustrating the effects of loss of wheel tread material due to wear or wheel re-profiling and the resulting redistribution of residual stresses.

Results of this study indicate that the initial residual compressive stress present in the wheel rim can be reversed to tension under nominal operating conditions. As it is known that such reversal can lead to the formation and growth of thermal cracks originating at the wheel tread, and that such cracks can pose a threat to safe rail operations, the ability to predict the influence of service conditions on wheel residual stresses becomes a useful tool for assessing proposed changes to operating characteristics.

Index terms: commuter wheel, residual stress, stress reversal

1. INTRODUCTION

This paper illustrates application of the shakedown residual stress estimation technique to assess the effects of service conditions on wheel residual stresses. The examples described provide the technical details on how the technique is practically applied and typical results. Operational conditions representative of a commuter railroad have been used in the simulations. Results are presented for a baseline commuter vehicle illustrating the effects of loss of wheel tread material due to wear or wheel re-profiling and the resulting redistribution of residual stresses.

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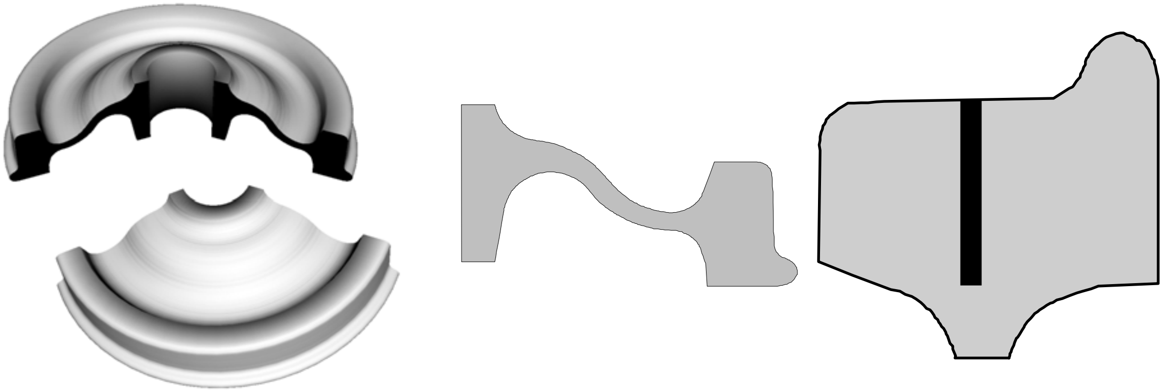
Stress reversal (from hoop compression to tension) is a well-known cause of thermal cracking and fracture in freight car wheels which have been subjected to repeated drag braking for long time at low power, but in such cases the stress is usually reversed in the bulk of the rim, most of which is heated to high temperature. Conversely, typical stop-braking profiles involve high power for short time and tend to flash-heat the outer rim region to temperatures much higher than those in the bulk of the rim. The thermal stresses, which are induced by temperature gradients, then concentrate in the outer rim region. Thus, wheel thermal response to stop-braking is not necessarily indicated by its response to drag-braking. Also, any subsequent drag-braking may cause rapid propagation of thermal cracks which have formed under less severe conditions.

2. WHEEL DESIGN AND INITIAL CONDITIONS

The design chosen for this analysis, an 81.3 cm (32-inch) diameter S-plate wheel, is representative of the wheels in use in commuter rail fleets. The S-plate acts as a radial spring, allowing the rim to expand and contract during heating and cooling without inducing excessive radial stresses in the plate. Figure 1(a) is a three-dimensional rendering of the subject wheel design and Figure 1(b) shows the cross-section of the wheel in the orientation that will be used for plotting the analysis results. Figure 1(c) shows the wheel rim in the position chosen for presentation of the distribution of residual stresses along the heavy line extending from the tread surface.

Estimation of the effects of service conditions on wheel residual stresses must account for the as-manufactured residual stress distribution. A finite element simulation of the quenching process of a wheel based on engineering estimates of the most important manufacturing variables is used to represent the quenching residual stresses [1].



(a) 3-dimensional rendering. (b) Cross-section. (c) Line through rim along which data is plotted.

Figure 1. Wheel geometry.

Following forming, the subject wheels are rim-quenched with a water spray for two minutes. The quenching operation occurs when the wheel is at 871 °C (1600 °F). The water quenchant is applied to the wheel tread region only. The quench is followed by a four-minute dwell at room temperature which accounts for the movement of the quenched wheel into the annealing furnace. The six-hour annealing portion of the heat treatment occurs at 500 °C (932 °F), after which the wheel is allowed to cool to room temperature. The entire process requires about 10 hours to complete. For the purposes of this study, the process described above is considered "present practice." The full details of the analysis, including a discussion of variants on present practice, are reported in [1].

The mesh used in this analysis is shown in Figure 2. The model consists of 1066 axisymmetric 4-node quadrilateral elements and 1131 nodes. A dense region of smaller elements at the wheel tread is intended to capture the contact and thermal stress gradients that are expected to occur at that location. Figure 3 is a close-up of the wheel rim that reveals the layering of elements below the tread surface. The layers are employed during the simulation of wear and reprofiling.

The "as-manufactured" residual stress distribution at the end of the quenching process is residual circumferential (hoop) compression at the wheel tread extending approximately 4 cm (1 inch) into the rim. The maximum magnitude of this compressive hoop stress is ~210 MPa (30 ksi) at the tread surface.

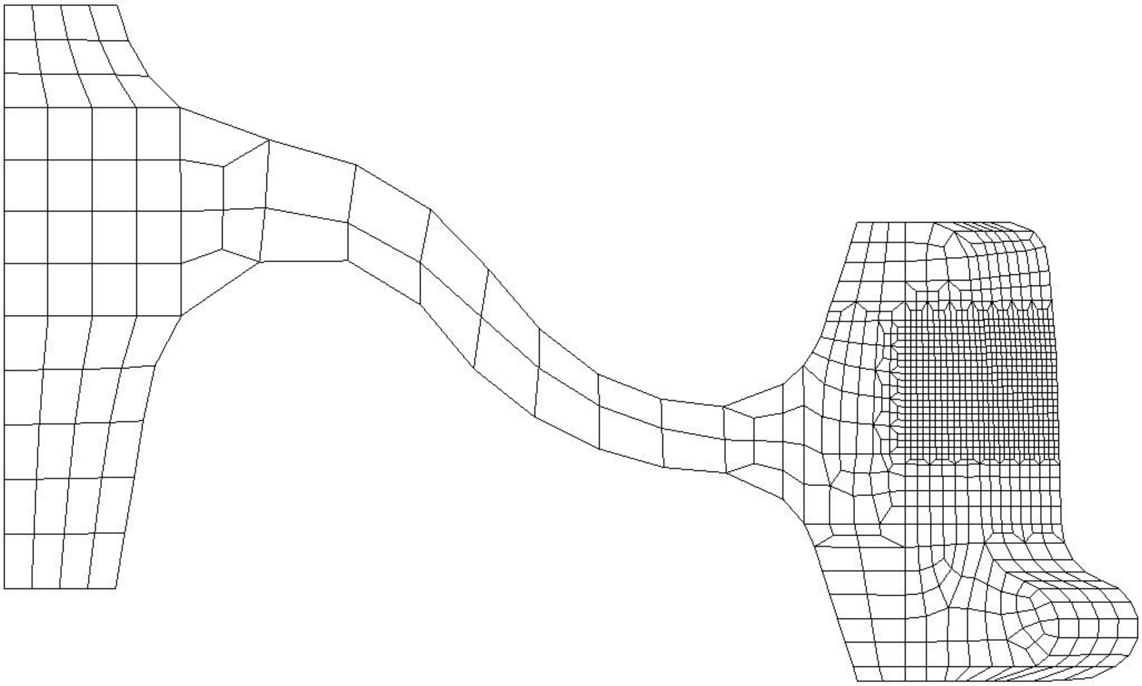


Figure 2. Finite element mesh for wear/re-profiling analysis.

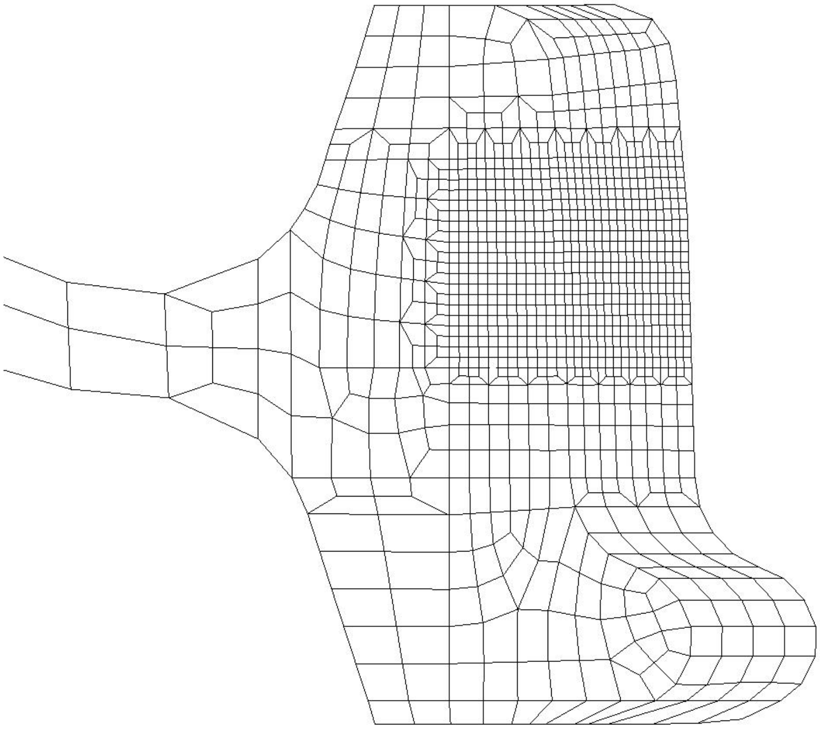


Figure 3. Finite element mesh for wear/re-profiling analysis - close-up of wheel rim.

3. SIMULATED SERVICE CONDITIONS

The effects of service conditions (contact loading and on-tread friction braking) are simulated using the shakedown approach based on the methods originally developed by Orkisz et al. for estimation of residual stresses in rail [2]. Holowinski and Bobrov [3] modified the technique to accommodate the analysis of stresses in wheels. The details of the analysis procedure [4] are summarized here.

The shakedown method combines the elastic stresses due to contact loading and braking, with the initial distribution of the as-manufactured stresses to approximate the residual stresses which result after repeated loading – that is, an estimate of how those service conditions influence the initial residual stress distribution.

To apply the technique, the elastic stress distribution due to contact loads and thermal stresses from friction braking must be calculated. Wheel/rail contact is assumed to result in a bi-parabolic pressure distribution applied over a contact patch whose size is related to the local radii, elastic material properties of the wheel and rail and the magnitude of the contact load. For an axisymmetric model of the wheel, a Fourier series approach is used to estimate the elastic stresses due to contact.

Thermal stresses from friction braking are obtained using the finite element model of the quenching process. It is modified to allow estimation of the transient temperature and stress distribution resulting from the heat flux generated at the brake shoe/wheel tread interface. This approach was developed to assess the effects on wheel temperatures of potential modifications to the braking systems of typical commuter vehicles [5]. Time- and temperature-dependent boundary conditions are applied to approximate the thermal input and losses which have been correlated with field measurements of wheel temperatures during actual stop-braking tests [6]. The heat flux is applied to a 6.35 cm (2.5 in) region centered on the wheel tread which represents the brake shoe contact area.

The input conditions for the contact and braking simulations are essential characteristics of the candidate vehicle and the assumed operating scenario. These parameters appear in Table 1.

Table 1. Simulation parameters.

PARAMETER	VALUE SI (English)
Wheel load	77.84 kN (17,500 lb)
Wheel diameter	81.3 cm (32 in)
Rail size	132RE
Speed	160 kph (100 mph)
Deceleration rate	0.8 to 0.9 m/s^2 (1.7 to 2 mph/s)
Stop time	52.4 s
Maximum instantaneous brake power	0.24 MW (320 hp)
Fraction of heat flux applied to wheel	95%

4. EFFECTS OF WEAR AND RE-PROFILING

The objective of this study is to develop an understanding of how changes of rim thickness may affect the shakedown residual stress distribution and to evaluate a short cut procedure for calculating shakedown stresses in thin rims. Rim thickness is reduced over the life of a wheel, either by gradual abrasive wear from wheel/rail contact during service, or because the rim is periodically machined to remove thermal cracks. Initial stresses, created in the subject wheel by means of rim quenching, are distributed through 6.35 cm (2.5 inches) of the new rim. Present maintenance standards allow these wheels to remain in service, if not cracked, until the rim thickness has decreased to 3.33 cm (1.3125 inches). In practice, railroads work with an extra margin of thickness to avoid the possibility that a rim might wear to below the 3.33 cm (1.3125 inch) condemning limit between scheduled inspections. As a result, wheels are usually scrapped when a rim thickness less than 3.81 cm (1.5 inches) is found by scheduled inspection.

4.1 Analysis Strategy – Multi-stage Procedure

A simulation of the thickness change effect can be done in a multi-stage analysis. Wheel shakedown stress calculations are alternated with conventional finite element calculations employing "dying elements." The latter method uses nodal force superposition to numerically cancel the boundary stresses between adjacent rows of elements, creating a free boundary at the interface between the rows.

The first simulation establishes a baseline for evaluation of the short cut procedure, discussed later. The operating conditions for this baseline simulation appear in Table 1. The first step of the strategy involves determination of the as-manufactured residual stresses in a new wheel prior to service as described in the previous section.

Next, the elastic stress distribution due to wheel/rail contact is calculated. In this analysis, the position of the contact load is confined to the area over which the brake shoe extends. It is understood that wheel/rail contact can occur at other locations on the tread, but since this study is concerned with the rim stresses in the vicinity of the tread, limiting the contact loads to the brake shoe band is sufficient. The contact load is swept across the wheel tread at eight positions within this band to account for the fact that wheel rail contact may wander due to variations in the profiles of the wheel or rail.

The elastic thermal stresses due to stop braking are determined next. This analysis assumes a full service stop from 160 kph (100 mph). The braking event is divided into eight increments in time. For each increment, the thermal stresses and temperature-dependent material properties are determined for each element in the model.

The shakedown approach is applied using the as-manufactured residual stress distribution as an initial distribution, with the contact and thermal stresses superposed. The shakedown model produces an estimate of the modified residual stress distribution due to the imposition of the service stresses.

The wheel, with the service-modified residual stress distribution is next represented when it has been reprofiled to remove approximately 0.64 cm (0.25 in) of rim material.

This thickness represents the average depth of thermal cracks which were observed in the wheels of a commuter car fleet during an inspection [7]. The target elements are removed from the model and the residual stresses redistribute to re-establish equilibrium. The finite element mesh was designed to maintain approximately the same height of flange above the wheel tread at each stage of the simulation.

This two-step sequence is repeated until the wheel reaches its condemning limit. In this analysis, four 0.64 cm (0.25 in) layers may be removed prior to the wheel acquiring a "thin rim" condition. The analysis strategy is represented as a block diagram in Figure 4.

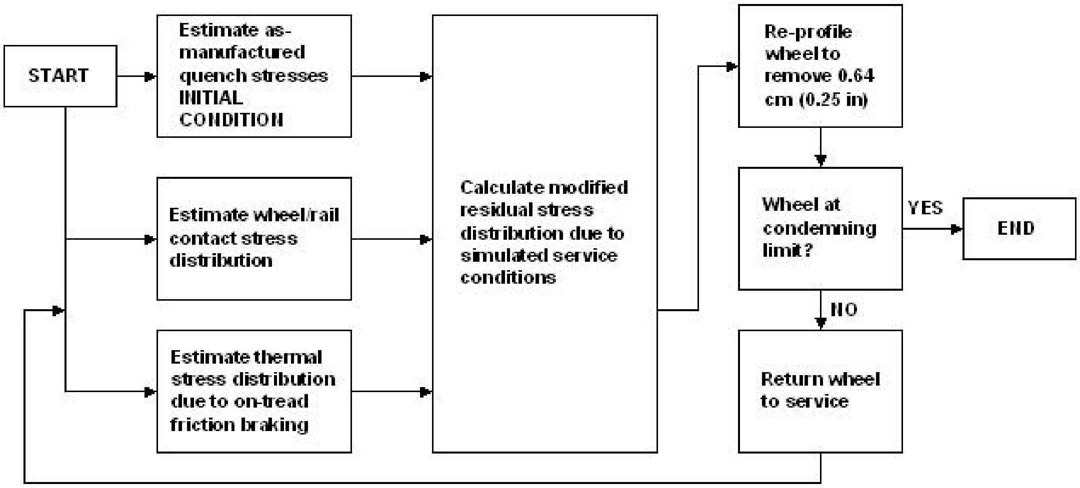


Figure 4. Analysis sequence.

4.2 Results

The modified residual stress distribution is depicted in Figure 5 at the end of the first stage of the analysis. Figure 5 shows contours of hoop residual stress in a new wheel subjected to the simulated service conditions described earlier. A region of residual tension appears at the wheel tread.

Figure 6 shows how the hoop stress is distributed along the line through the rim shown schematically in Figure 1(c). The vertical axis denotes depth below the tread surface (0 cm). The horizontal scale represents the magnitude of residual hoop stress in MPa (6.895 MPa = 1 ksi). The dashed horizontal lines denote the depths of the four layers of wheel rim material which will be removed in the subsequent calculations.

The blue curve in Figure 6 represents the as-manufactured condition. The red curve shows how these stresses are modified due to the imposition of the service (contact and thermal) stresses. The residual compression at the tread surface (210 MPa, 30 ksi) is reversed to tension (340 MPa, 50 ksi). The tensile layer extends approximately 0.6 cm (0.24 in) from the tread surface. The residual compression increases slightly from the as-manufactured level just below the tensile zone.

The green curve illustrates how this hoop residual stress profile is modified after removal of one 0.64 cm (0.25 in) layer. The simulated reprofiling completely removes the tensile layer, leaving the newly-exposed tread surface in compression but of a magnitude significantly lower than was present following manufacture (62 MPa, 9 ksi). The reprofiling also results in a modest decrease in the maximum residual compression which was present following application of the service loading. This occurs approximately 0.6 cm (0.25 in) below the new tread surface. Deeper into the rim, the effects of the service loading and reprofiling diminish quickly. The stresses here differ little from the initial as-manufactured distribution, confirming that the influence of service loading on the residual stress distribution is confined to a very shallow layer near the tread surface.

Figure 7 and Figure 8 present the corresponding information after the second layer is removed. The results are similar to those which appear in Figure 5 and Figure 6. Service loading causes reversal from tension to compression with a corresponding increase in the maximum compression below the tensile layer. Reprofiling removes the tensile zone and reduces the maximum compression below.

Figures 9 through 12 show the stress distribution after the third and fourth layers are removed. The results clearly begin to follow a pattern. As each tensile layer is removed, the residual compression present at the newly-formed tread surface increases slightly from the previous iteration.

Finally, Figure 13 and Figure 14 contain the stress results for a wheel which has worn to the condemning limit and been re-exposed to the service loading sequence. This wheel will likely soon be removed due to its thin rim condition. The residual compressive zone between the stress-reversed layer at the surface and the residual tension in the lower portion of the rim has been reduced in thickness and magnitude as a result of the repeated reprofiling. This implies reduced capacity of this rim to tolerate tread cracking. Cracks which form at the tread surface under these conditions may grow at a faster rate than those which occurred when the rim thickness was greater.

4.3 Analysis Strategy – Short-Cut Procedure

The detailed procedure described above is extremely tedious and time consuming to execute in practice. Elastic stress distributions for each of the eight contact load positions and thermal stress distributions for each of the eight intervals during the simulated stop must be calculated. These calculations are repeated for each of the four rim thicknesses.

In order to expedite the process, consideration is given to an abbreviated analysis strategy. The short cut procedure is based on an assumption that the effects of service stresses (wheel/rail contact and thermal stress) dominate over effects of thickness reduction. Beginning again with the baseline initial manufacturing stresses, the new wheel undergoes simulated service by applying the contact and thermal stresses as was done in the first analysis. The "dying element" method is used to simulate an immediate decrease of rim thickness from 6.35 cm to 4.81 cm (2.5 to 1.5 inches). That is, all four layers are removed at once. The shakedown stress state is then recalculated for the 4.81 cm (1.5 inch) rim, using the modified initial stresses but with other inputs the same as those used in the final step of the multi-stage analysis. The results are discussed in the next section.

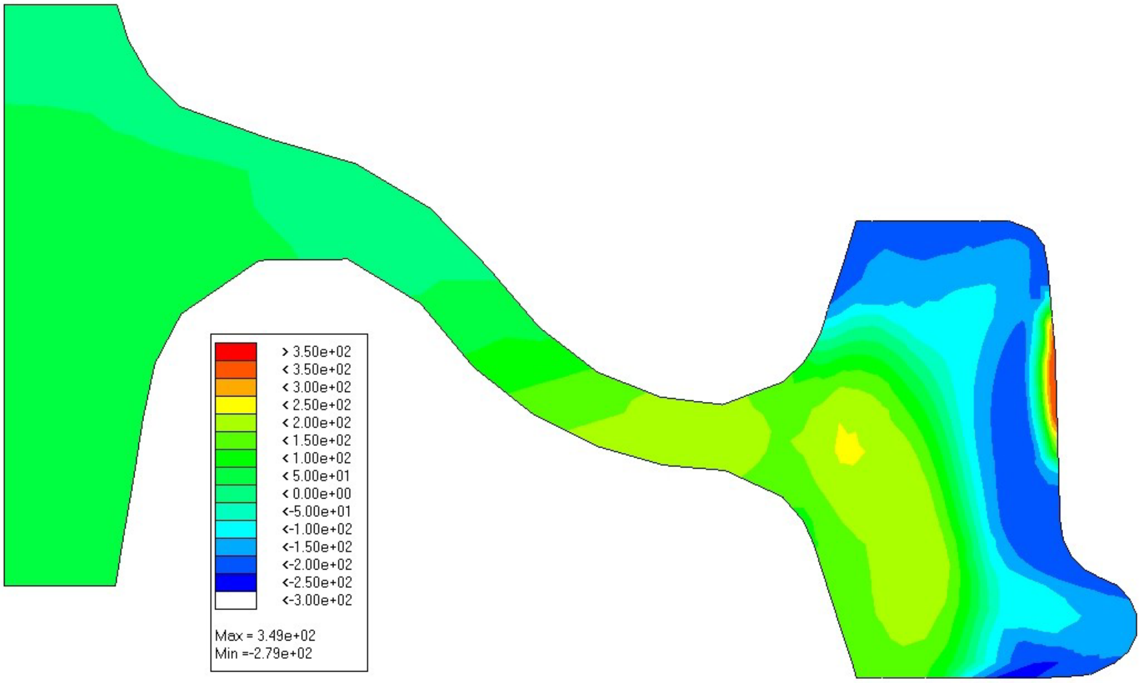


Figure 5. **Hoop stress contours after simulated service - new wheel (MPa).**

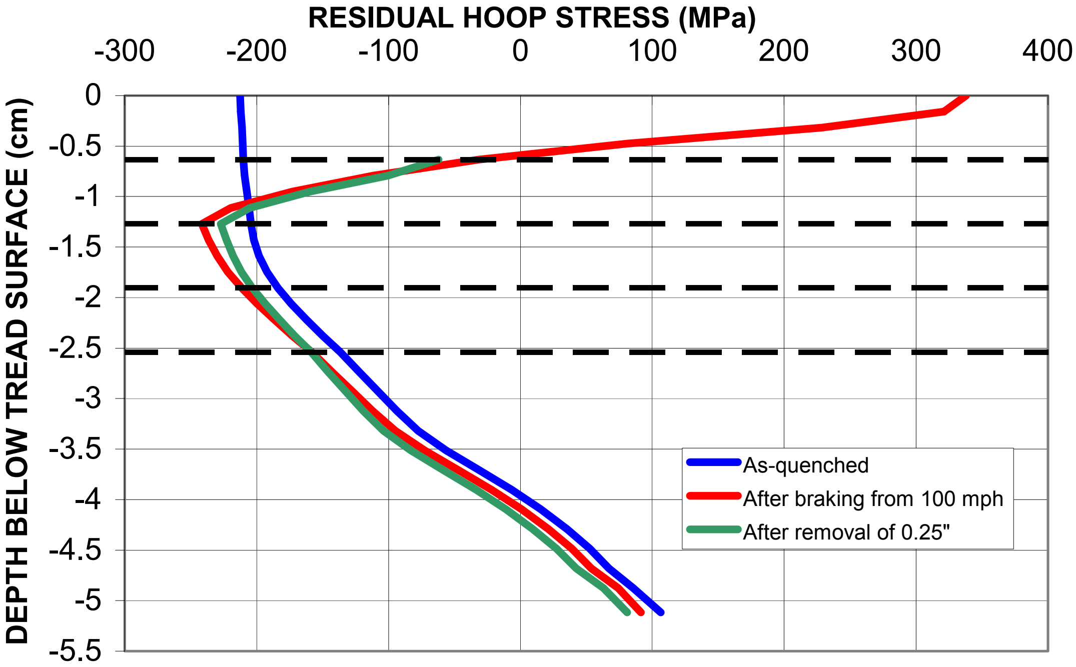


Figure 6. **Hoop stress distribution after simulated service and removal of first layer.**

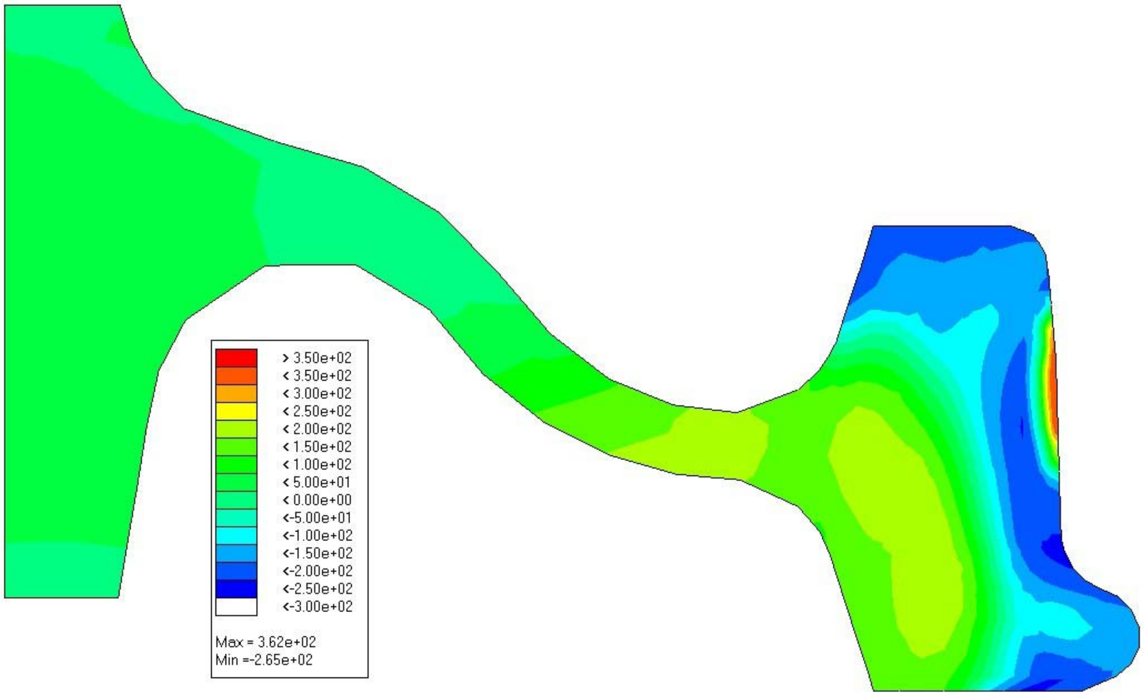


Figure 7. Hoop stress contours after simulated service following removal of first layer (MPa).

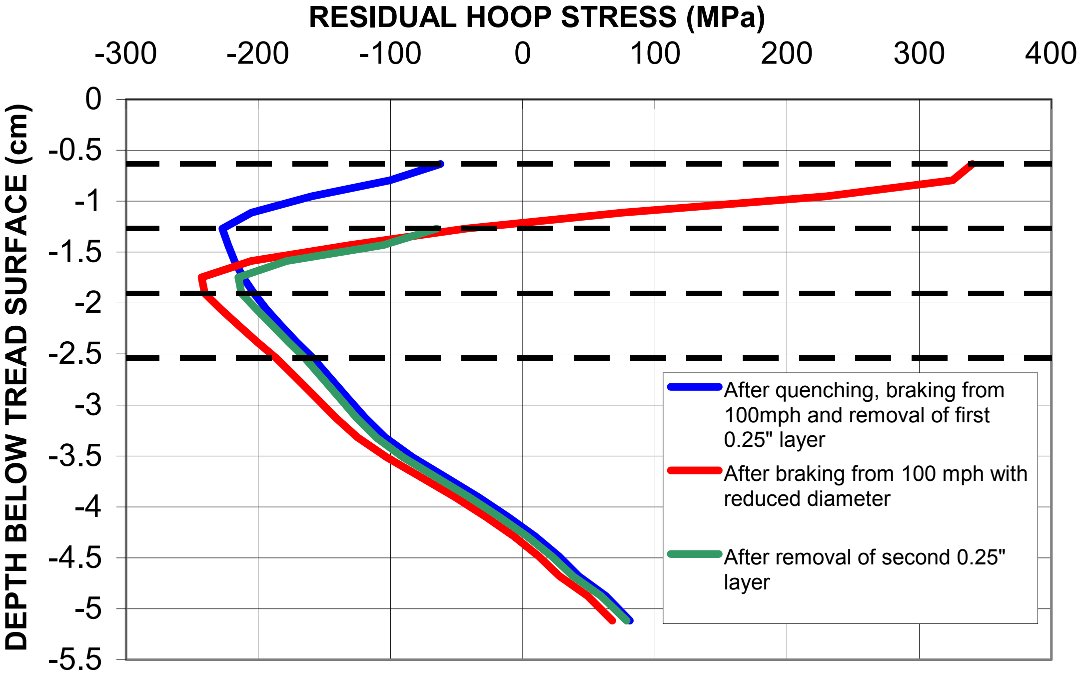


Figure 8. Hoop stress distribution after simulated service and removal of second layer.

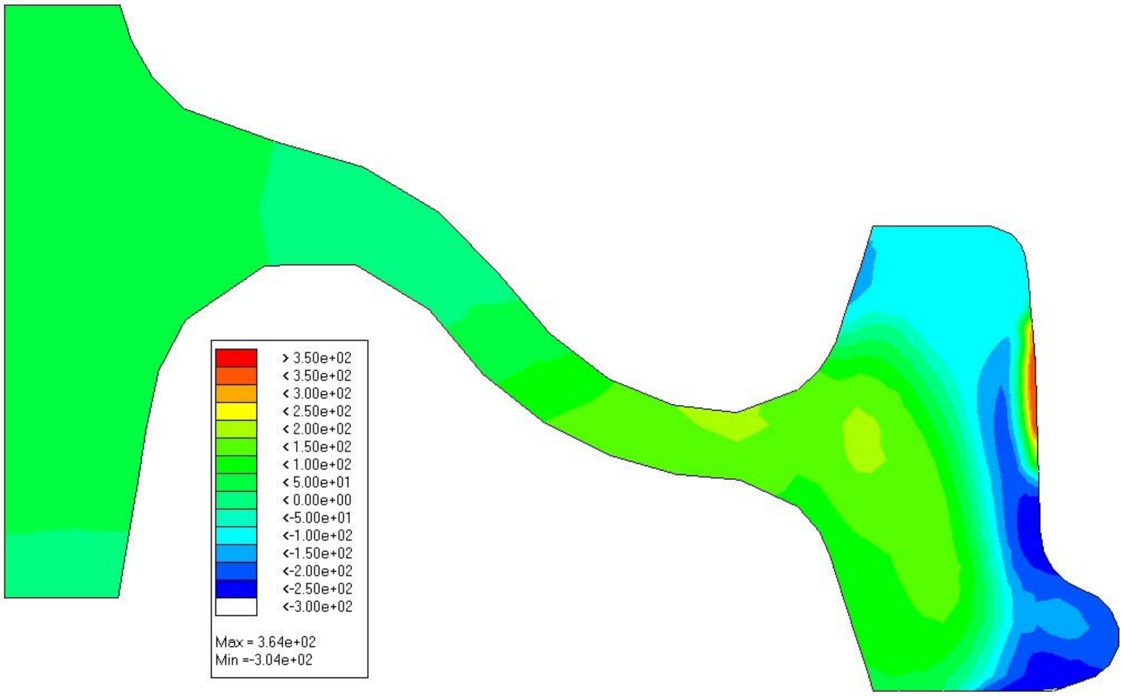


Figure 9. Hoop stress contours after simulated service following removal of second layer (MPa).

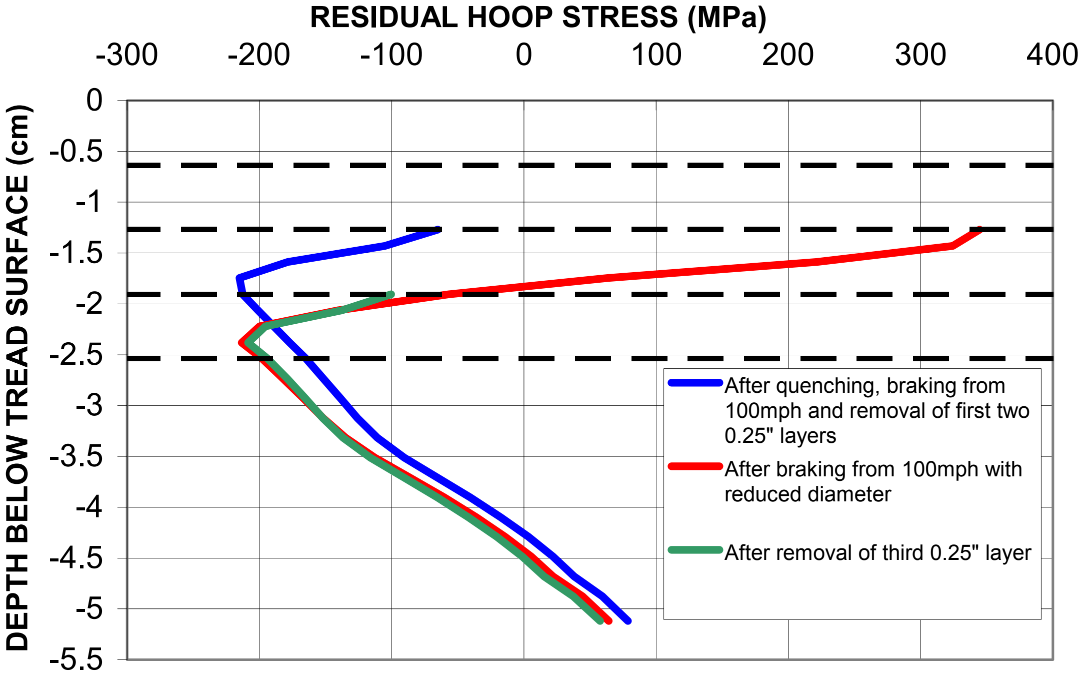


Figure 10. Hoop stress distribution after simulated service and removal of third layer.

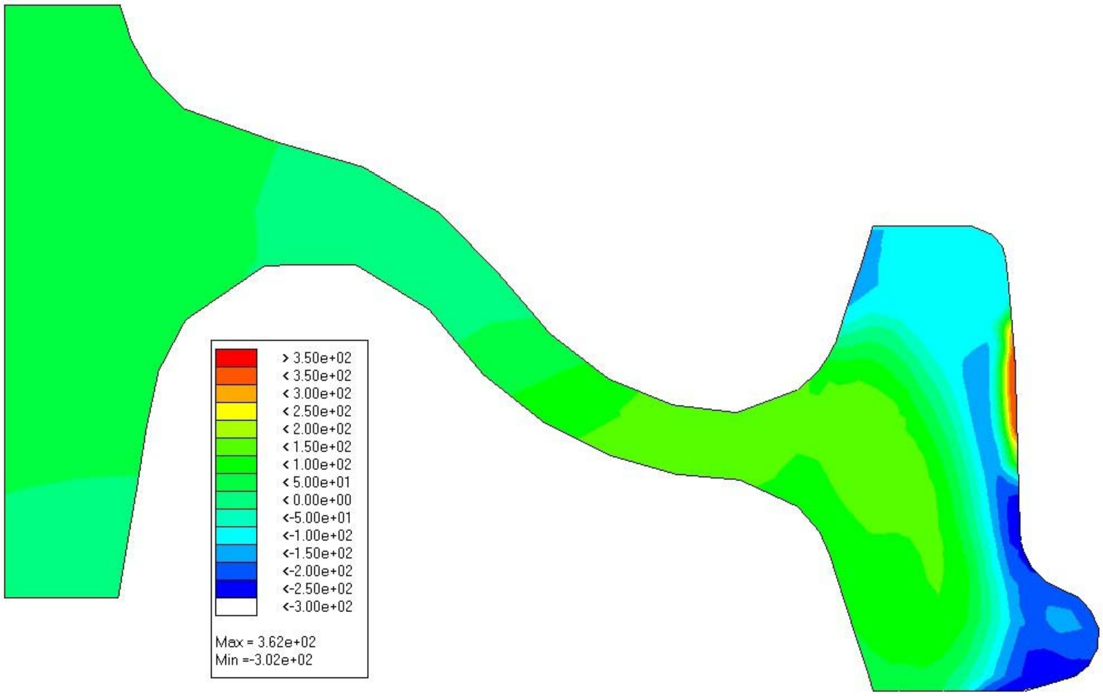


Figure 11. Hoop stress contours after simulated service following removal of third layer (MPa).

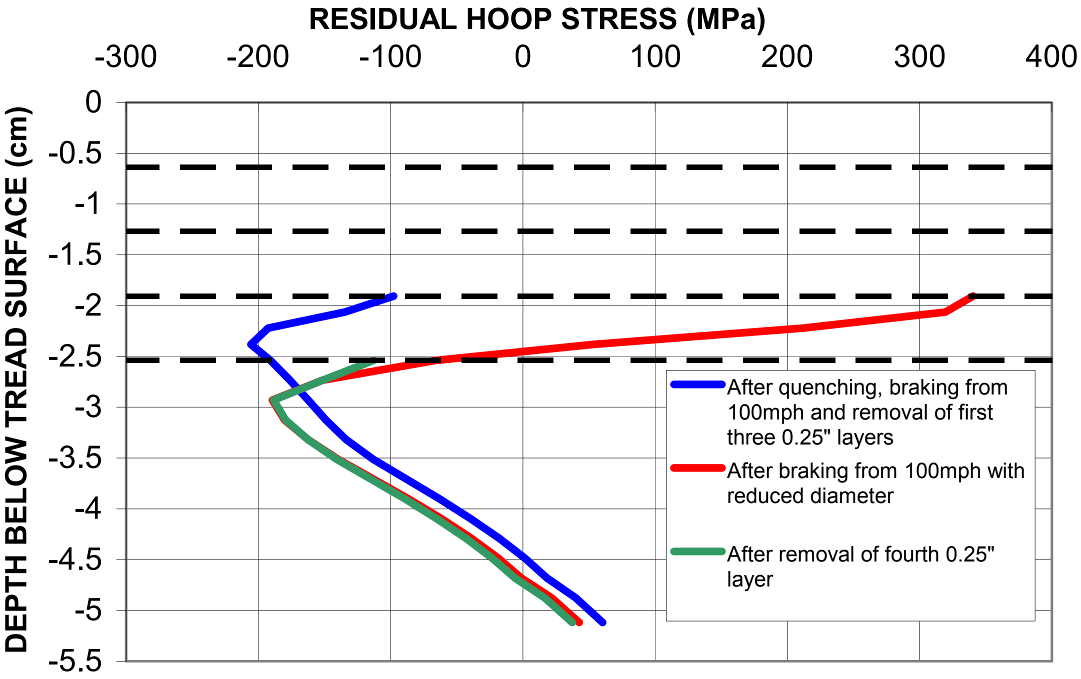


Figure 12. Hoop stress distribution after simulated service and removal of fourth layer.

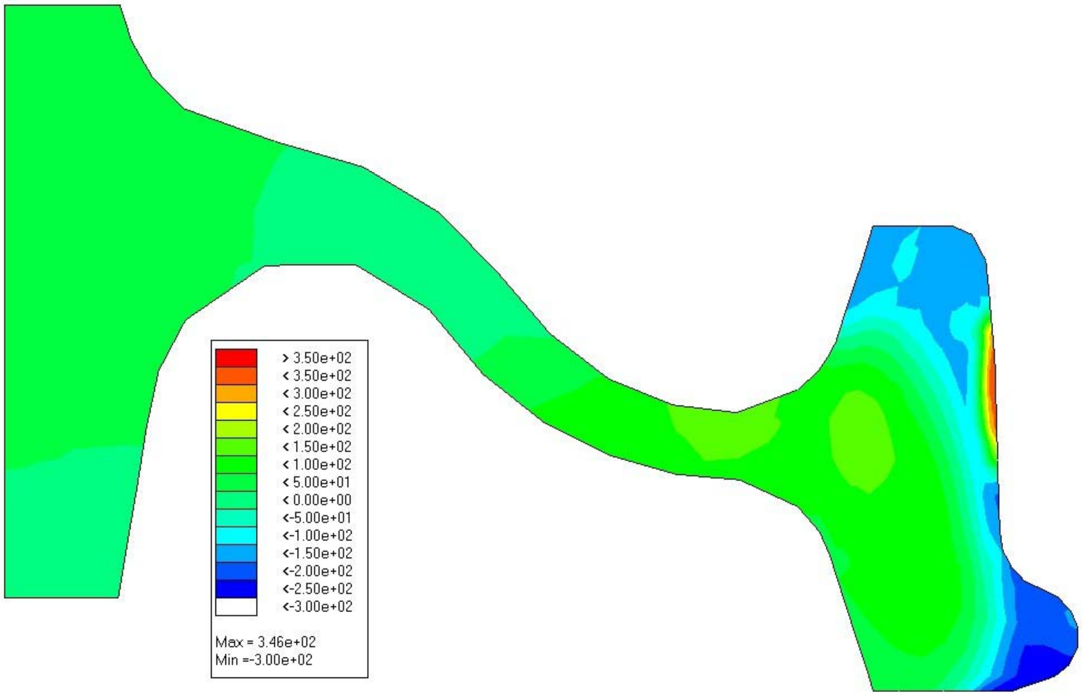


Figure 13. Hoop stress contours after simulated service following removal of fourth layer (MPa).

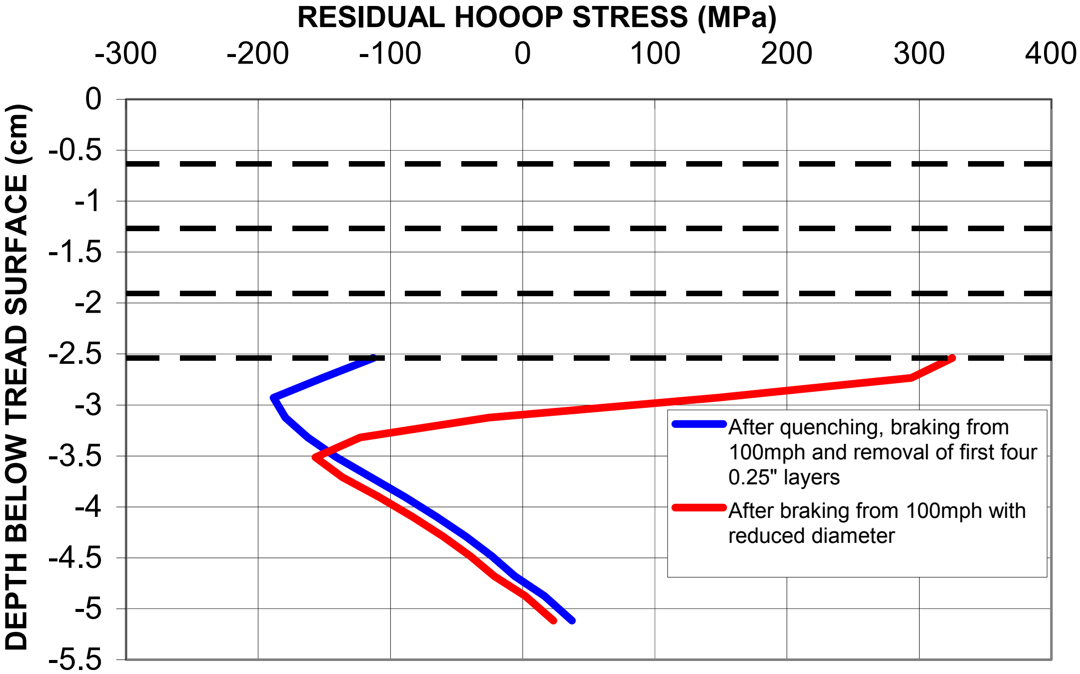


Figure 14. Hoop stress distribution after simulated service at condemning limit.

5. DISCUSSION

5.1 Detailed Multi-stage Analysis

Exposure of the wheel to service conditions (specifically the high thermal stresses induced by braking) results in the formation of a layer of tensile residual stress in the rim, regardless of its thickness. This is especially apparent in Figures 5 to 14 which depict the stress profile at each stage in the simulation. As each layer is removed and the contact and braking loads are reapplied to the wheel, a tensile layer approximately 0.63 cm (0.25 in) thick reappears.

The results of the multi-stage analysis are summarized in Figure 15. At each step in the process of “wearing” a wheel from the new condition to its condemning limit, the residual stress distribution retains the general characteristics acquired when the wheel is first subjected to service loading.

As the rim material is gradually removed, the residual hoop stress at the tread surface remains compressive (a benefit from the point of view of crack formation and growth). However this compression is significantly lower in magnitude than the compressive stress which exists following manufacture.

Further, as the rim thickness approaches the condemning limit, the maximum residual compression in the rim is reduced. The net effect of this is an overall reduction in the magnitude and extent (depth of penetration) of residual compression in the rim.

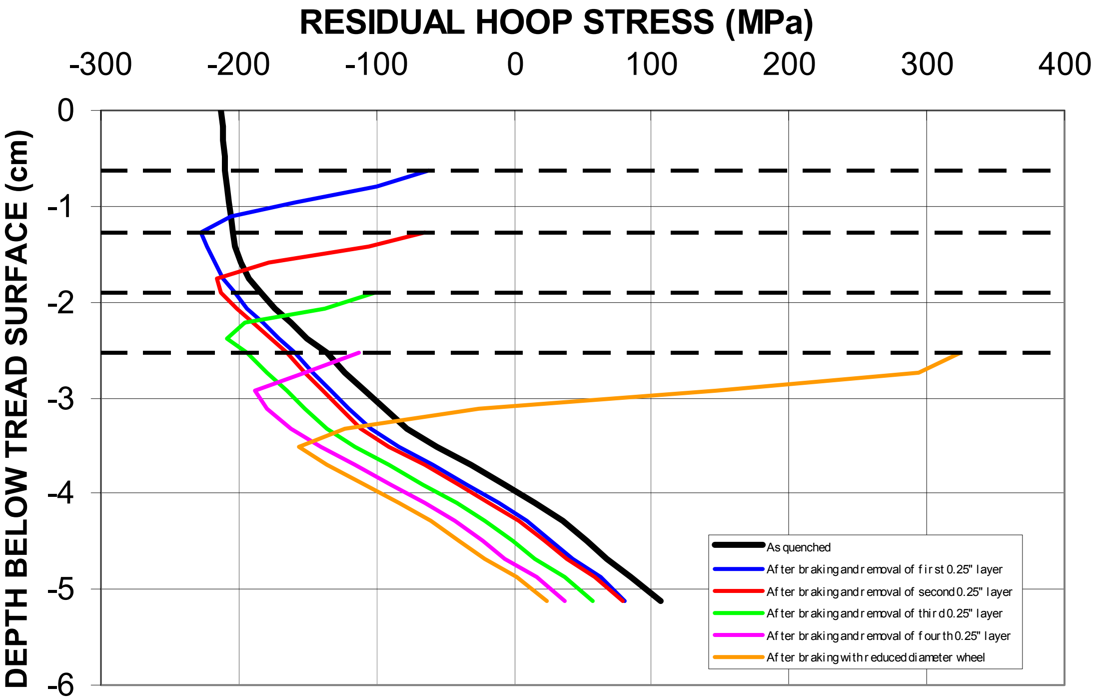


Figure 15. Hoop stress distribution after simulated service and removal of all layers.

5.2 Short-cut Procedure

Figure 16 combines the final results of the multi-stage analysis and the short-cut procedure. Comparison of the final results for the two approaches indicates that there is very little difference between the detailed four-step analysis and the more efficient short-cut scheme. Near the tread surface the results are practically identical. Deeper into the rim, the short-cut method predicts only slightly greater maximum residual compression. The shakedown residual stress estimation tool applied using the short-cut procedure can be used to estimate wheel rim stress reversal.

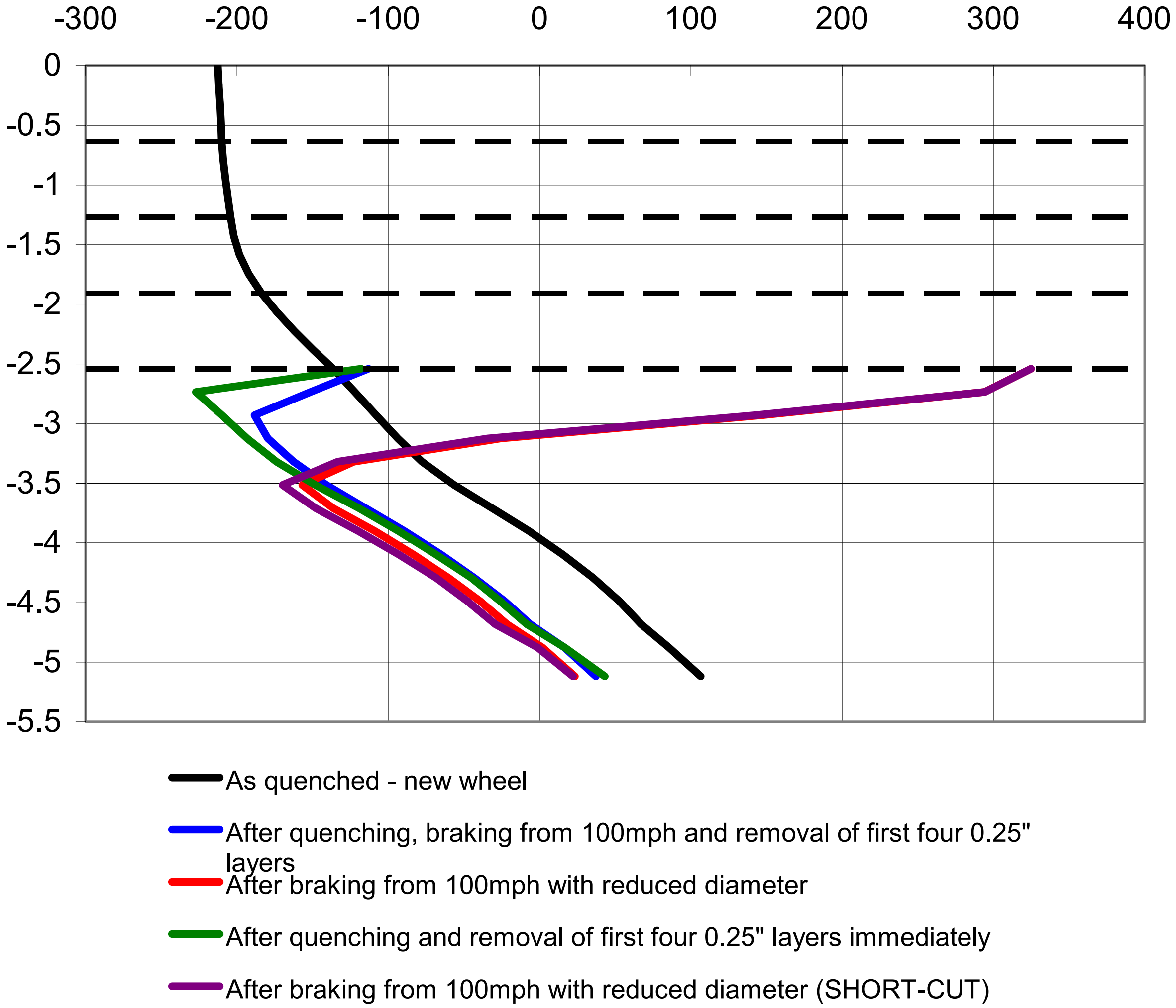


Figure 16. Results of short-cut procedure.

6. CONCLUSIONS

This paper assesses the effects of wear using a multi-stage analysis and a simpler short-cut procedure. The analysis techniques have been applied previously to predict rim stress reversal in wheels of commuter fleet subjected to high-performance stop braking. The depth of stress reversal has been correlated with measurements made on thermally-cracked wheels removed from service.

The results indicate that the loss of compressive residual stress in the rim as it wears from the “new” condition to the fully-worn condemning limit may increase the likelihood of thermal cracking. The bulk residual compression, which is present following manufacture, is diminished substantially as the wheel rim thickness is reduced. The risk of thermal cracking is an important consideration for fleet operators as it relates to potential changes in operational characteristics such as increased speed or modifications to train braking demands (such as station spacing or deceleration rate).

The short-cut approach described in sections 4.3 and 5.2 provides comparable estimates of residual stresses to those obtained with the more labor-intensive layer-by-layer methodology. This is an important finding as it now allows exploitation of the analysis tool to more efficient evaluation of the effects of different equipment operating characteristics.

7. ACKNOWLEDGEMENT

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