Design of Proof Rolling Regimes for Heavy Duty Aircraft Pavements

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ABSTRACT: Proof rolling of aircraft pavements is an Australian practice that is designed to reveal pavement layer deficiencies prior to the construction of the next pavement layer. There are a number of heavy pneumatic-tyred proof rollers available in Australia for this purpose. These rollers are predominantly owned by the Department of Defence and made available to airfield constructors, on a project-by-project basis. The selection of rollers and the design of proof rolling regimes should utilise the stress with depth calculation function of layered elastic design tools such as APSDS. Proof rolling regimes can be determined by comparison of aircraft and roller induced plots of the damage indicator with depth. The traditional use of Boussinesq's equation for simple load stress with depth in a single elastic layer is also viable for many practical applications. Strain and deflection could also be used as the damage indicator but stress is the most effective as the pavement structure, subgrade strength and location of the damage indicator have little effect on the calculated stresses. A single layer representation of the pavement is also adequate. More specific cases, where the absolute values of the damage indicator are required or where non-typical pavements are to be designed, a customised pavement structure may be justifiable for the roller and aircraft induced stress calculations.

KEY WORDS: Proof rolling, Heavy aircraft pavements, Layered elastic design.

1 INTRODUCTION

Proof rolling of heavy duty aircraft pavements during their construction is generally practiced in Australia. With the introduction of large commercial aircraft, such as the B767 and B747, extra heavy duty proof rolling equipment was designed and built by the Australian Commonwealth Department of Housing and Construction from the 1950s.

The aim of proof rolling these heavy duty pavements is to expose the various layers to a level of 'damage' (indicated by calculated stress, strain or deflection) that is slightly greater than the maximum expected service 'damage', prior to constructing the next layer of the pavement structure. By proving pavements in this manner, the variability of the structural strength of the pavement is significantly reduced, allowing thinner pavements to be constructed with equal reliability.

The design of proof rolling regimes therefore comprises two steps:

- Calculating the values of the chosen indicator of damage at various depths through the pavement layers.

- Selection of a proof rolling regime (mass and tyre pressure combination) to be applied to the various layers of the pavement structure such that the calculated maximum service damage indicator value is just exceeded.

This paper presents the development of proof rolling as a key element of the construction of heavy duty aircraft pavements in Australia. The Australian layered elastic design tool for aircraft pavement thickness determination is used as an example of a tool for the calculation of stress, strain and deflection with depth. Finally, the effectiveness of the layered elastic design tool in determining proof rolling requirement is demonstrated and example proof rolling regimes are presented.

2 PROOF ROLLING FLEET

The Australian Department of Defence owns eleven pneumatic-tyred heavy aircraft pavement rollers. The first two of these rollers were purchased and imported from the USA in the 1950s (Brown, 1966). These rollers, known as Macro rollers, were capable of applying up to 50 t on four wheels with a tyre pressure of up to 1.4 MPa. The Commonwealth then constructed, a number of additional Macro rollers, based on the US roller design, of which seven remain operational.

One of these Macro rollers was converted to 50 t on two wheels, with tyre pressures up to 1.65 MPa. The roller was designed to produce stresses comparable to those induced by heavier commercial aircraft and high tyre pressure military jets. This roller was known as the Test Rig. At around the same time, the Commonwealth also constructed a number of 200 t rollers on four wheels, with up to 1 MPa tyre pressure, known as the Porter Supercompactor. Only one Porter Supercompactor remains in services in Australia today. These Porter Supercompactor rollers were specifically designed for the compaction of deep dredged-sand fills and for proving of subgrades to large depths.

3 DAMAGE INDICATOR CALCULATION

In 1996, MINCAD Systems first released the aircraft pavement specific version of CIRCLY, titled Aircraft Pavement Structural Design System (APSDS) (MINCAD, 2000). The layered elastic component of the design tool is used for the calculation of the damage (stress, strain or deflection at the critical points) induced by a single load application. Many other layered elastic aircraft pavement design tools are also available for the generation of these pavement damage indicators.

During each design scenario, the layered elastic design tool algorithms calculate the stresses, strains and deflections of the pavement at a range of depths, as well as at user defined lateral and longitudinal coordinates. The ability to view all damage indicators calculated at all pavement locations is not available in all layered elastic tools and is one advantage of APSDS. This provides for the ability to easily generate plots of stress, strain and deflection against depth under the aircraft wheels or between aircraft wheels.

In developing a methodology for the design of proof rolling regimes, the damage indicator calculation options include:

- Stress, strain or deflection as the indicator of pavement damage caused by aircraft and rollers.
- Use of the actual pavement structure or a simple single layer of material.
- Use of actual or representative subgrade strength value for all subgrades.

- Calculation of the damage indicator directly under a tyre or at the centre of a wheel gear, or both.

4 DEFLECTION, STRESS AND STRAIN

Prior to the development of APSDS and other layered elastic pavement design tools, proof rolling regimes were developed using stress as the damage indicator. Pre-generated charts for aircraft and various proof rollers were compared to determine the proof rolling regime. Pre-determined charts were used as their generation was time consuming and these charts were generally developed using Boussinesq's (1885) formula for stress in a single elastic layer imposed by a simple static load. The use of stress curves generated by single point loads and uniform, single layer, pavement structures was not by choice but due to the lack of any more accurate tool being available at the time. Practitioners hoped that the forced simplifications were valid but this assumption remained untested. With the advent of layered elastic design tools, the ability to generate stresses, strains and deflections at a range of depths for complex loads and complex pavement structures is readily available. Therefore, the options for comparing aircraft and roller induced 'damage' is markedly expanded.

To compare the relative merits of using stress, strain or deflection as the indicator of damage for proof rolling regimes, stresses, strains and deflections were calculated under a B737 aircraft (between the tyres and directly under one tyre) and plotted against depth for the following pavement structures:

- 1000 mm crushed rock base course material on CBR 6.
- 1000 mm crushed rock base course material on CBR 15.
- 1000 mm natural gravel sub base material on CBR 6.
- 1000 mm natural gravel sub base material on CBR 15.

The resulting plots of damage indicator with depth are shown in Figures 1 to 3 for stress, strain and deflection respectively.

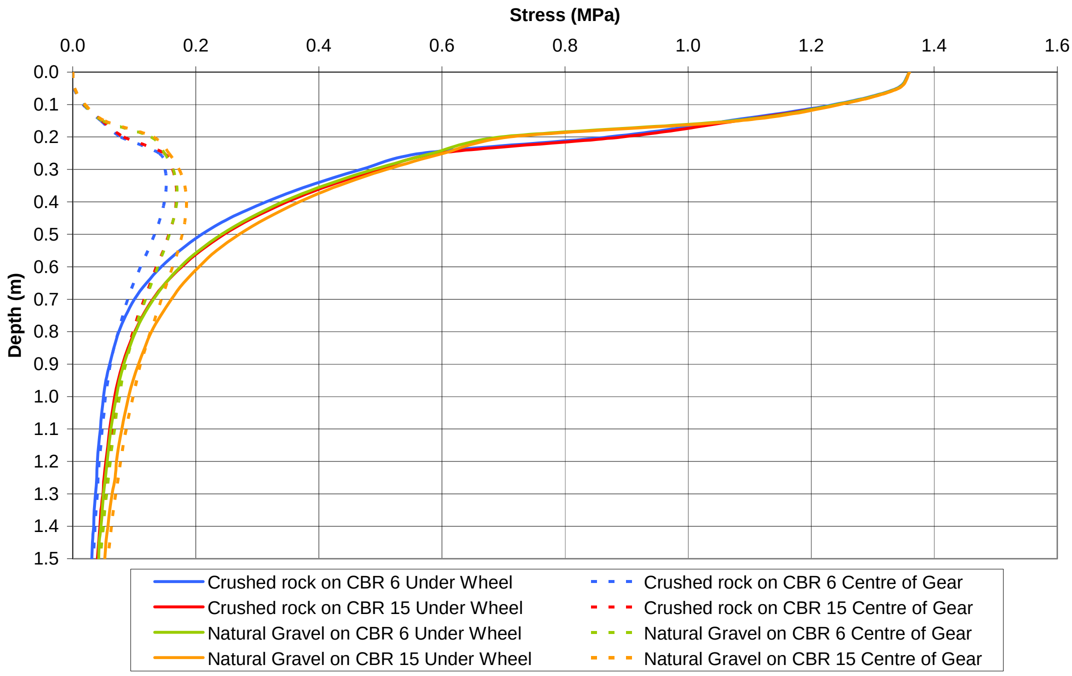

Figure 1: B737 Vertical Stress with depth for various pavements.

From Figure 1 it can be seen that stress at the pavement surface is equal to the tyre pressure (under a wheel) and zero between two tyres. At depth (in this case below 0.8 m), stresses beneath and between the wheels are similar in all cases. Irrespective of the pavement material adopted and the subgrade strength selected, the stresses are similar at all depths.

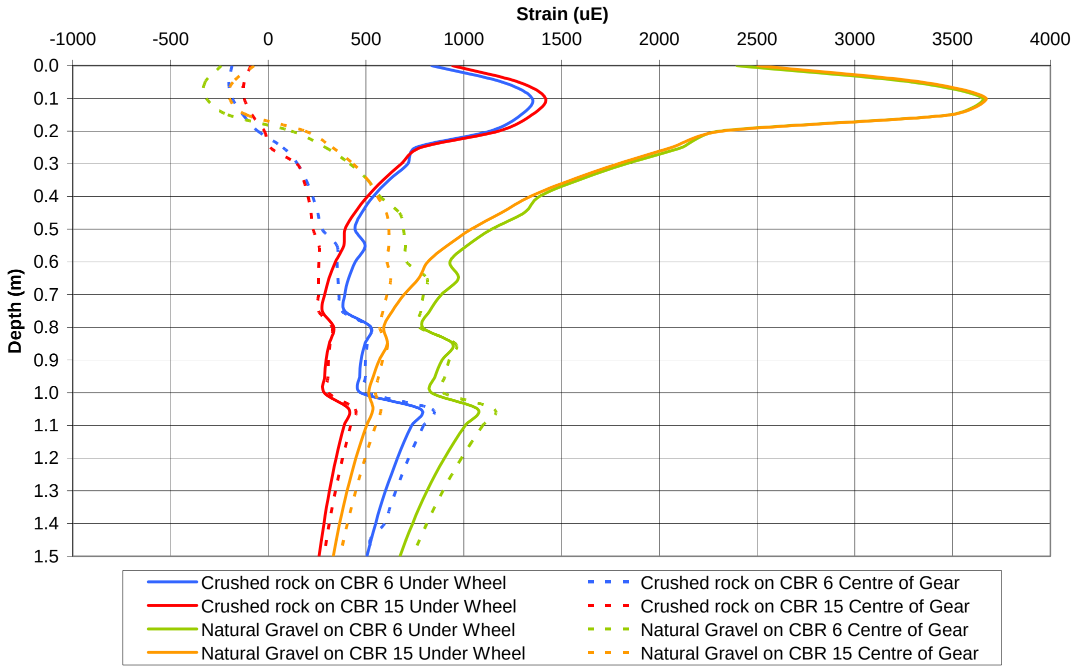

Figure 2: B737 Vertical Strain with depth for various pavements.

From Figure 2, it can be seen that strains vary significantly with pavement material as well as subgrade strength. Strains also show complex relationships to depth and are less consistent than stress. They cannot readily be related to aircraft loading (tyre pressure and load) at either the surface or at depth. Further, at changes in pavement layers and sub-layers, strains increase sharply due to a continuously and smoothly decreasing stress and an immediate (discontinuous) decrease in modelled material modulus.

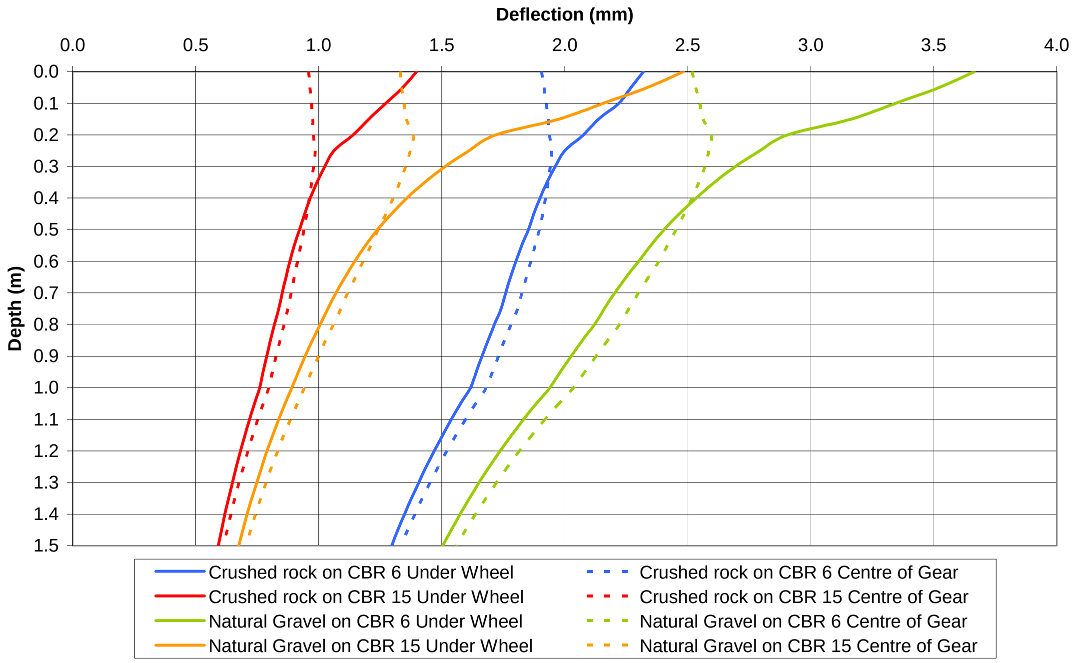

Figure 3: B737 Vertical Deflection with depth for various pavements.

Deflections with depth are shown in Figure 3 to be simple in their shape but vary significantly with subgrade strength and pavement material. There is also comparatively small difference in the deflection at the top of the pavement to that at depth.

Based on the analysis of Figures 1 to 3, stress is selected as being the preferred method for indicating damage in the design of proof rolling regimes. Stress is selected as it provides the following advantages:

- Easy to visualise and understand compared to strain.
- Equal to tyre pressure at the pavement surface.
- Related to load per landing gear at depth.
- Essentially equal for all modelled subgrade strengths and granular pavement materials.
- Essentially equal, at depth, under the tyre and in the centre of a multiple wheel landing gear.
- Decreases smoothly with increased depth from a maximum value at the surface.

It is also concluded from Figure 1 that stresses should be calculated directly under a tyre only. At the surface, the stress induced under a tyre is significantly higher than that at the centre of the landing gear. At depth the under-tyre and centre-gear stresses converge and whilst the centre-gear stress does exceed the under-tyre stress at depth, it is essentially equal for comparative purposes. The additional effort required to compare the greater of the under-tyre and centre-gear stresses is not considered warranted.

5 PAVEMENT COMPOSITION

Using stress under the tyre as the most appropriate indicator of damage, the influence of pavement structure was considered. From Figure 1, it can be seen that there is virtually no difference in the stress with depth for base or sub-base materials on either a strong (CBR 15) or weaker (CBR 6) subgrade. These stress with depth plots are shown in Figure 4 with the equivalent plot for a typical B737 capable pavement. The B737 pavement consisted of:

- 50 mm asphalt of 1500 MPa.
- 200 mm crushed rock base course material.
- 550 mm natural gravel sub-base material.
- CBR 6 subgrade.

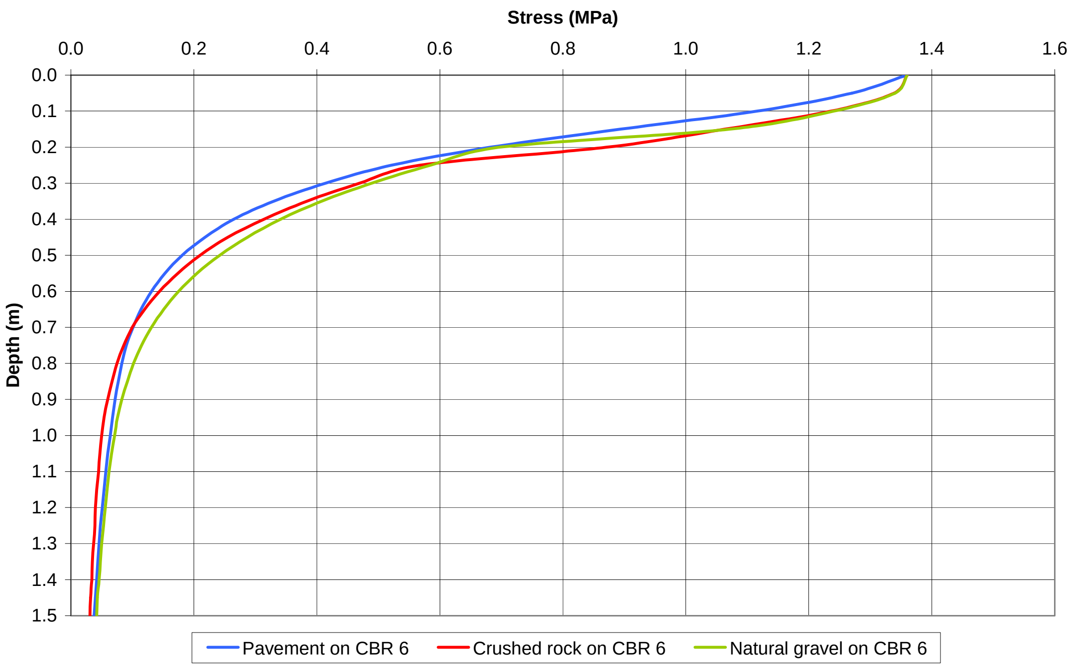

Figure 4: Comparison of Pavement and Single Material Stresses.

Significant variations from the B737 pavement adopted for the generation of Figure 4 were also assessed. This focused on the asphalt layer and included a higher modulus asphalt option (4000 MPa) and a thicker (200 mm – with the sub-base reduced to maintain a consistent total pavement thickness) asphalt layer option. A combined high modulus, thick asphalt option was also assessed. The comparison of the stress with depth for each asphalt option is illustrated in Figure 5.

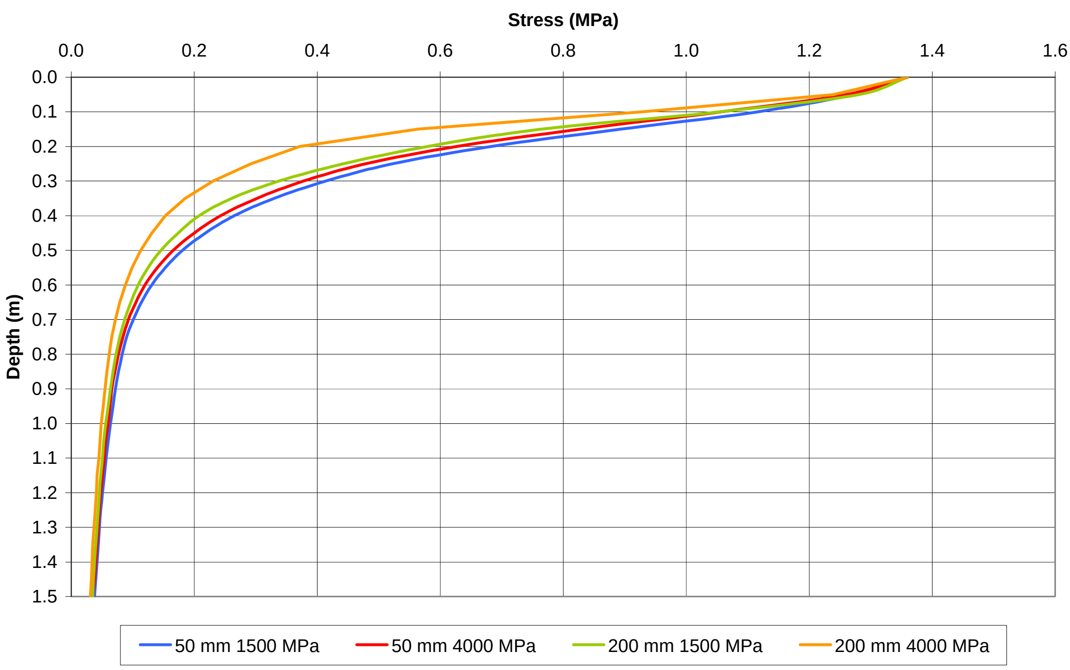

Figure 5: Asphalt thickness and modulus effects.

Figures 4 and 5 confirm the suggestion from Figure 1 that pavement structure (material and subgrade strength) have little impact on the stress with depth.

When it is considered that the proof rolling regime design is a comparison of relative stress induced by aircraft and roller, the influence of materials or pavement structure becomes even less important, as long as the same pavement structure is adopted for both the aircraft and roller stress calculations. Therefore, for practical purposes, a standard pavement of 1000 mm of crushed rock base course on CBR 6 subgrade is selected for stress with depth calculations. This selection is justified by:

- All materials having an essentially negligible differential effect.
- The relative or comparative (aircraft to roller) stress being more important than the accuracy of any absolute stress values.
- Base material having a modulus approximately equal to the mean of the moduli of asphalt and subgrade.
- CBR 6 being typical of many pavement subgrades at airports in Australia.

When absolute stresses or far from typical pavement structures are required, a customised pavement for the determination of stress with depth may be justified. Such a case may be the 200 mm thick of 4000 MPa asphalt surface layer option shown in Figure 5. However, as the roller and the aircraft stress with depth would be similarly affected by the non-standard pavement, it would be inconsequential to use a single layer pavement in most practical circumstances. Where required, customised stress with depth plots can readily be generated for any pavement structure using APSDS or other layered elastic tool. The customised pavement structure must be adopted for both the design aircraft and the proposed proof rollers.

6 ROLLER CONFIGURATION

There are three specifically designed roller types available in Australia for proving heavy duty aircraft pavements. More conventional pneumatic-tyred rollers can also be utilised but are less likely to induce stresses comparable to those caused by the design aircraft. For each roller, there is a range of acceptable mass and tyre pressure combinations (Defence, 2003) required to control tyre distortion. The allowable tyre pressure and roller mass combinations for the Macro, the Test Rig and the Porter Supercompactor are shown in Figures 6 to 8.

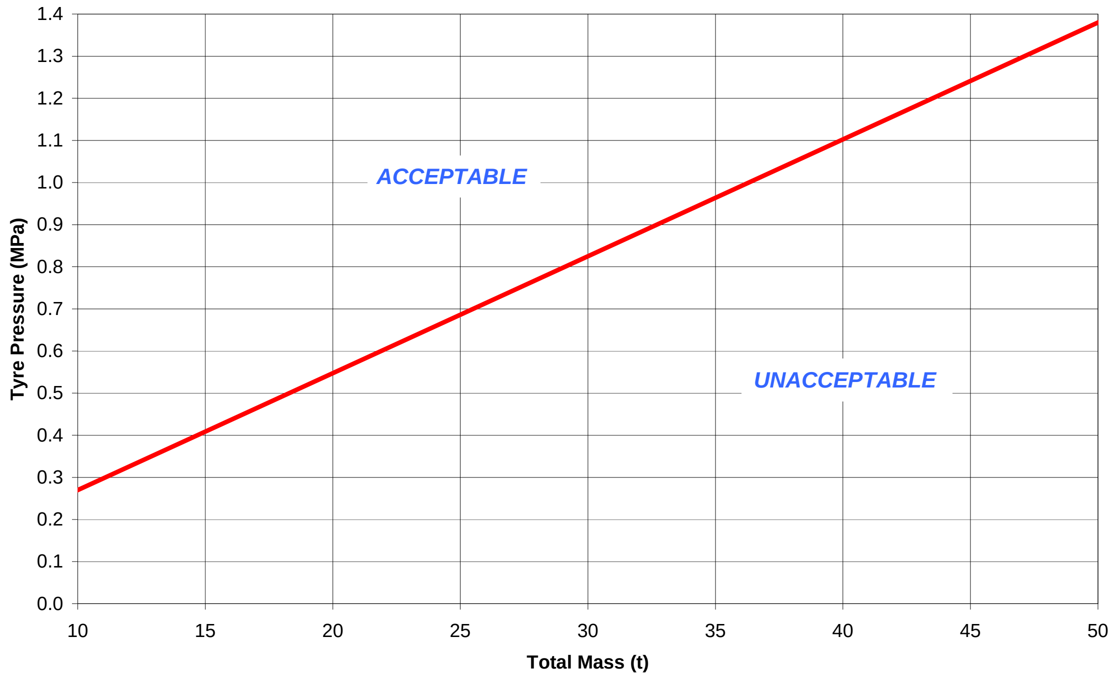

Figure 6: Allowable Macro Roller Tyre Pressures and Masses.

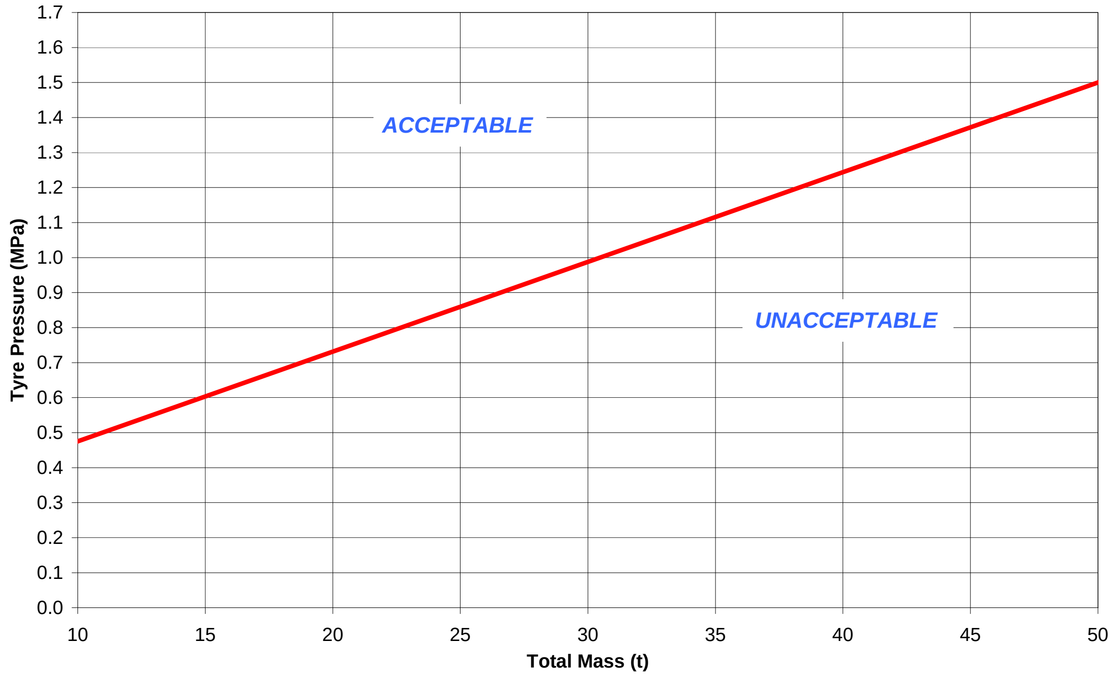

Figure 7: Allowable Test Rig Roller Tyre Pressures and Masses.

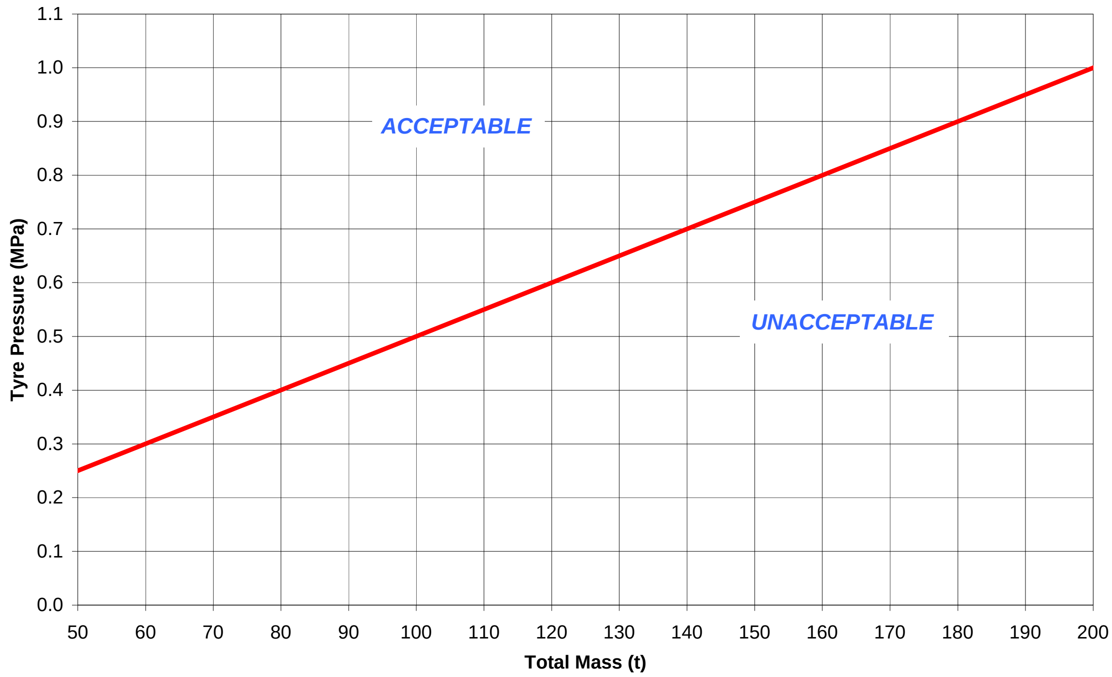

Figure 8: Porter Supercompactor Tyre Pressures and Masses.

The stress, directly under a tyre, with depth (at maximum mass and tyre pressure) for each of the three rollers is illustrated in Figure 9.

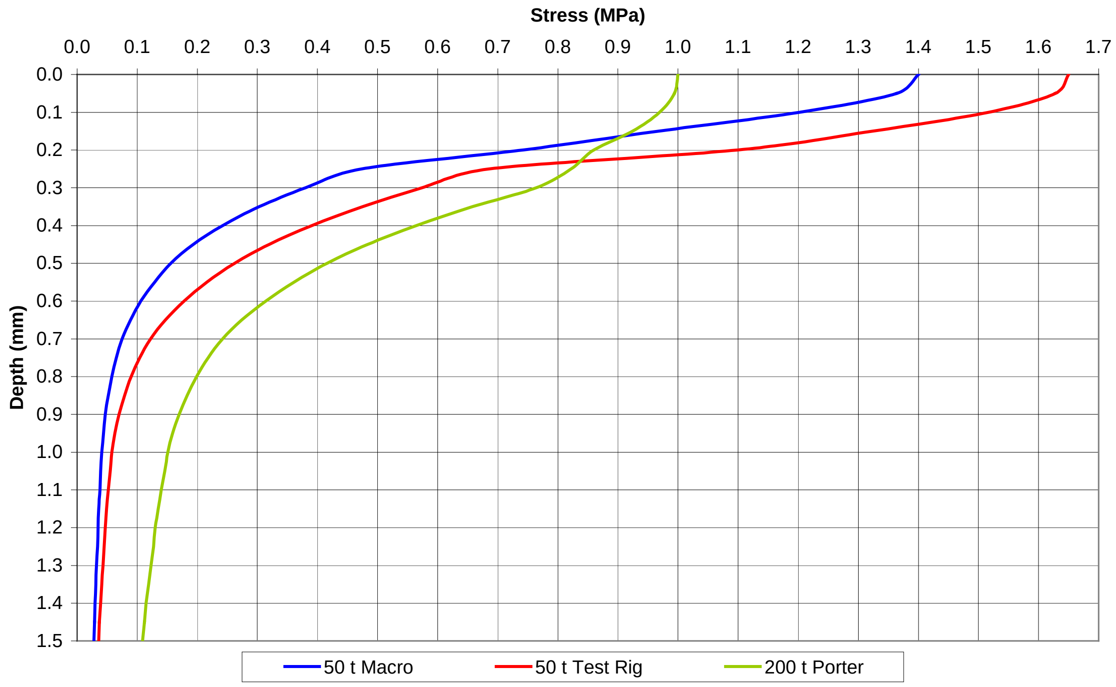

Figure 9: Vertical Stress with Depth for Various Rollers.

Figure 9 shows that at the pavement surface, the high tyre pressure of the Test Rig induces the greatest stress. At depth, the higher wheel load of the Porter Supercompactor results in the greatest stress. Due to their availability (through greater numbers), portability and versatility, the Macro is the most practical roller to use for most projects. Other rollers may be preferred for very large projects, specific project requirements or where they are locally available. Based on Figure 6, the maximum allowable roller mass for a range of tyre pressures can be determined for the Macro roller. The stress with depth curves for each allowable combination is shown in Figure 10. Figure 10 forms the basis of the roller induced stresses for a proof rolling regime design.

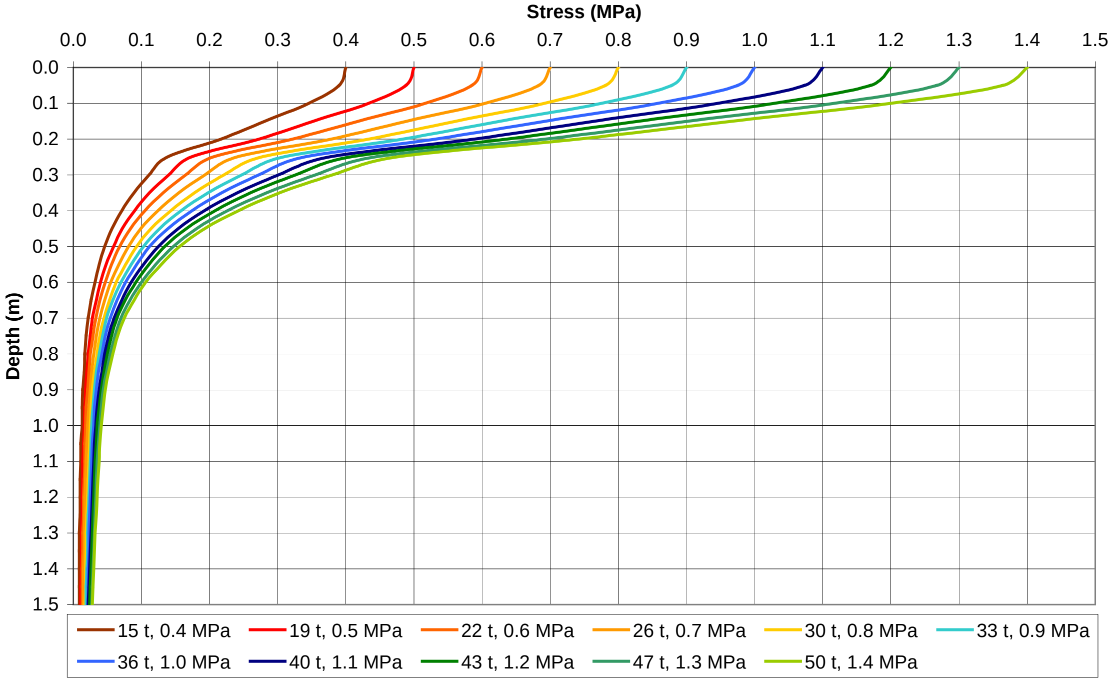

Figure 10: Macro Roller Vertical Stress with Depth at various roller masses.

The 'kinks' which can be seen for all rollers configurations at 0.25 m depth are caused by the large change in sub-layer modulus at this depth. The assigned change in sub-layer modulus is generated by the Barker and Brabston sub-layering system which is automated in APSDS.

7 PROOF ROLLING REGIMES FOR COMMON AIRCRAFT

The design of proof rolling regimes remains a comparison of stresses at depth modelled for the aircraft to those modelled for the selected roller. Roller configurations (mass and tyre pressure) are selected such that their calculated stresses are slightly larger than those for the aircraft. The aircraft induced stress of interest is that imposed by the design aircraft located on the finished pavement surface. However, the roller induced stress of interest is that resulting from the roller being placed directly on the layer being proved. Whilst the layers to be proved during construction is a subjective assessment, typically proving would occur at:

- Final subgrade level.
- On top of the sub-base course.
- On top of the base course.

Stress with depth plots for aircraft are generated by APSDS in a similar manner to that for the rollers. Figure 11 shows stresses with depth for the following aircraft:

- B747 at 397 t and 1.38 MPa. A dual-tandem landing gear.
- B767 at 180 t and 1.24 MPa. A dual-tandem landing gear.
- B737 at 78.5 t and 1.36 MPa. A dual wheel landing gear.
- F111 at 50.8 t and 1.48 MPa. A single wheel landing gear.

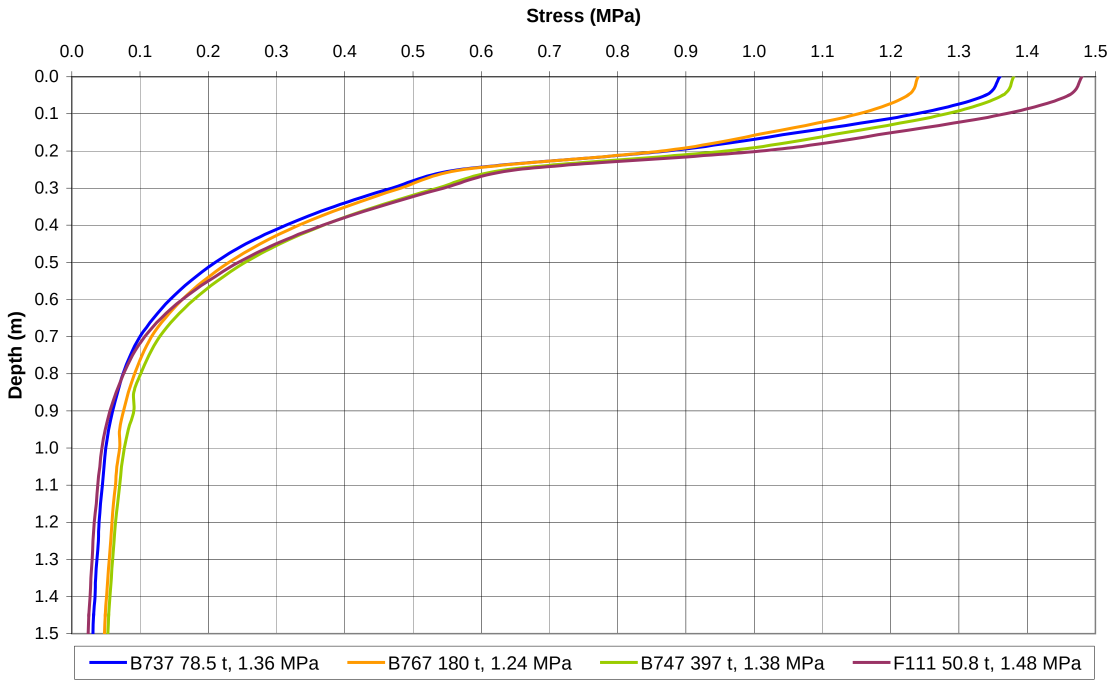

Figure 11: Vertical Stresses with Depth for various Aircraft.

These aircraft were chosen as they span the range of common medium to large civil and military jet aircraft in terms of landing gear configuartions, wheel loads and tyre pressures.

A proof rolling regime designed for any aircraft mix should accommodate the envelope of maximum stress induced by all the aircraft in the mix. For the four aircraft shown in Figure 11, the high tyre pressure of the F111 would govern in the upper layers whilst the B747's high mass per landing gear would dominate at the lower levels and subgrade.

The B767 is approximately half the mass of the B747 but has half the number of main wheels so induces similar stresses at depth to those of the larger aircraft. The B747 and B767 aircraft induce pressures at 1.2 m that are comparable to those induced by the F111 and B737 at around 0.9 m.

8 EXAMPLE ROLLING REGIME DESIGN

A proof rolling regime is to be determined for each of the individual aircraft whose stress with depth is illustrated in Figure 11. With the adoption of a standard pavement (1000 mm crushed rock base course material on CBR 6 subgrade) the only pavement specific issue needing to be considered is the layers (and their thickness) upon which the rollers are to be applied. The depth from the finished surface level determines the portion of the aircraft induced stress with depth plot to be considered. These are the stresses that need to be exceeded by the chosen proof roller for proving that layer of the pavement. For the B737 aircraft, the assumed pavement structure is as detailed for the derivation of Figure 4.

Based on the stress with depth plot for the B737 aircraft and the application of the proof rollers at finished subgrade, top of sub-base and top of base course levels, the proof rolling regime becomes:

- Subgrade. 22 t at 0.6 MPa.
- Sub-base. 36 t at 1.0 MPa.
- Base. 50 t at 1.4 MPa.

The stress with depth for the B737 aircraft and for the proof rollers (applied at each pavement layer) is shown in Figure 12. The roller masses and pressures were selected to allow the roller induced stresses to just exceed the aircraft induced stresses in each layer being proved. The asphalt surface layer is not proved because the required degree of compaction is only achievable when the asphalt mix is at placing temperature, typically around 150°C. Proof rolling at ambient temperatures would not correct low asphalt density or prove that the required asphalt density had been achieved during construction.

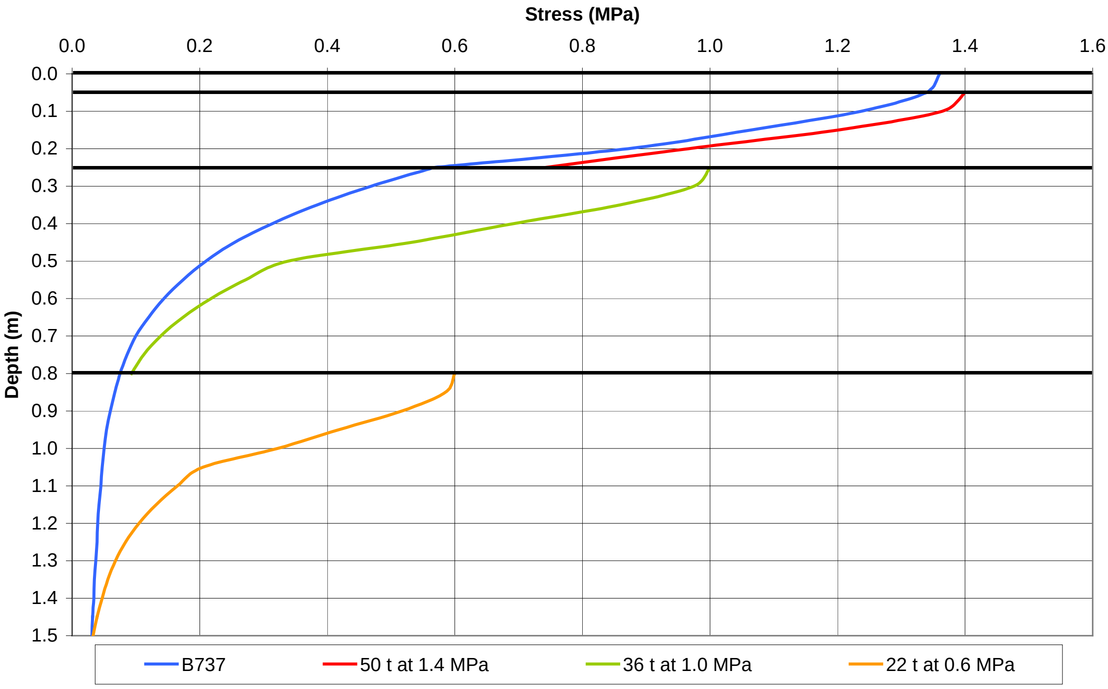

Figure 12: B737 proof rolling regime.

Proof rolling regimes were also determined for B767, B747 and F111 aircraft. It is noted that the pavement layer thicknesses needed to be determined in each case as this determines the levels at which the rollers are applied. Table 1 details the adopted pavement structures and proof rolling regimes for each of these aircraft (all with a 50 mm of 1500 MPa asphalt surface).

Table 1: Pavement structures and Proof Rolling Regimes for B767, B747 and F111.

Course	**B767**		**B747**		**F111**	
	Thick	**Roller**	**Thick**	**Roller**	**Thick**	**Roller**
Subgrade	NA	19 t 0.5 MPa	NA	30 t 0.8 MPa	NA	19 t 0.5 MPa
Sub-base	500 mm	26 t 0.7 MPa	400 mm	22 t 0.6 MPa	550 mm	30 t 0.8 MPa
Base	400 mm	22 t 0.6 MPa 50 t 1.4 MPa	400 mm	26 t 0.7 MPa 50 t 1.4 MPa	200 mm	50 t 1.4 MPa

Two rolling configurations are required for the B767 and B747 base courses as the Macro roller (at 50 t and 1.4 MPa) cannot match the aircraft induced stresses at the bottom of the base course when applied at the top. The first of the two roller configurations is applied to the bottom half of the base course and the second configuration to the top of the base course. This is appropriate as the 400 mm of base course would be placed in two layers in order to achieve adequate compaction.

The rolling regimes and the associated stresses with depth, for the B767, B747 and F111 aircraft, are illustrated in Figures 13 to 15.

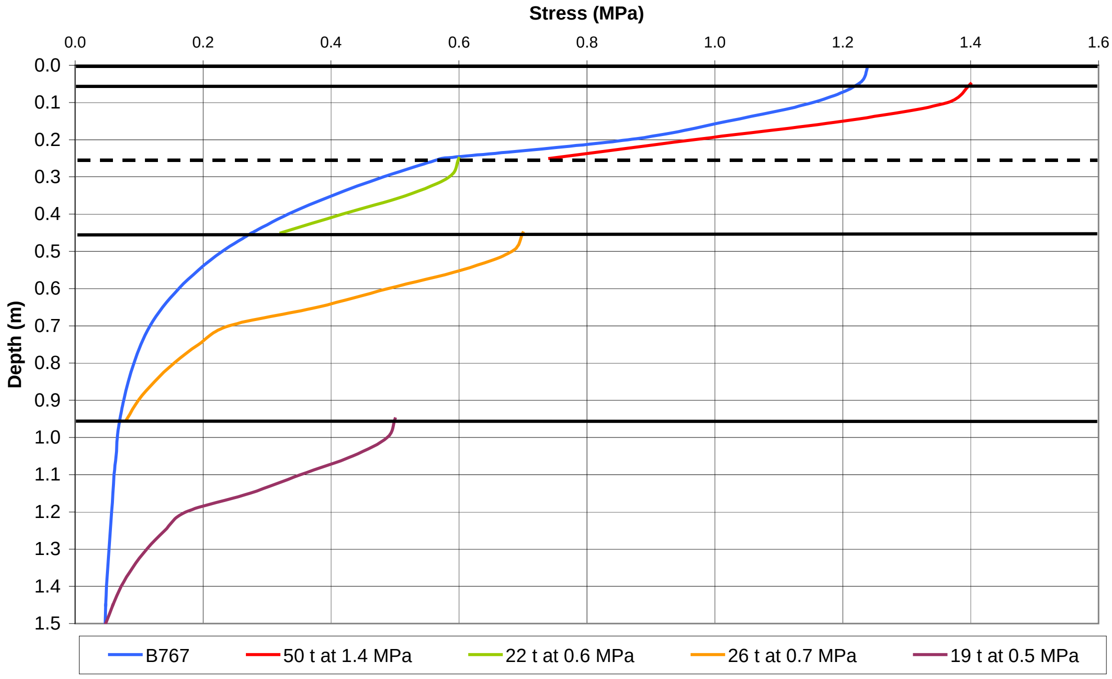

Figure 13: B767 proof rolling regime.

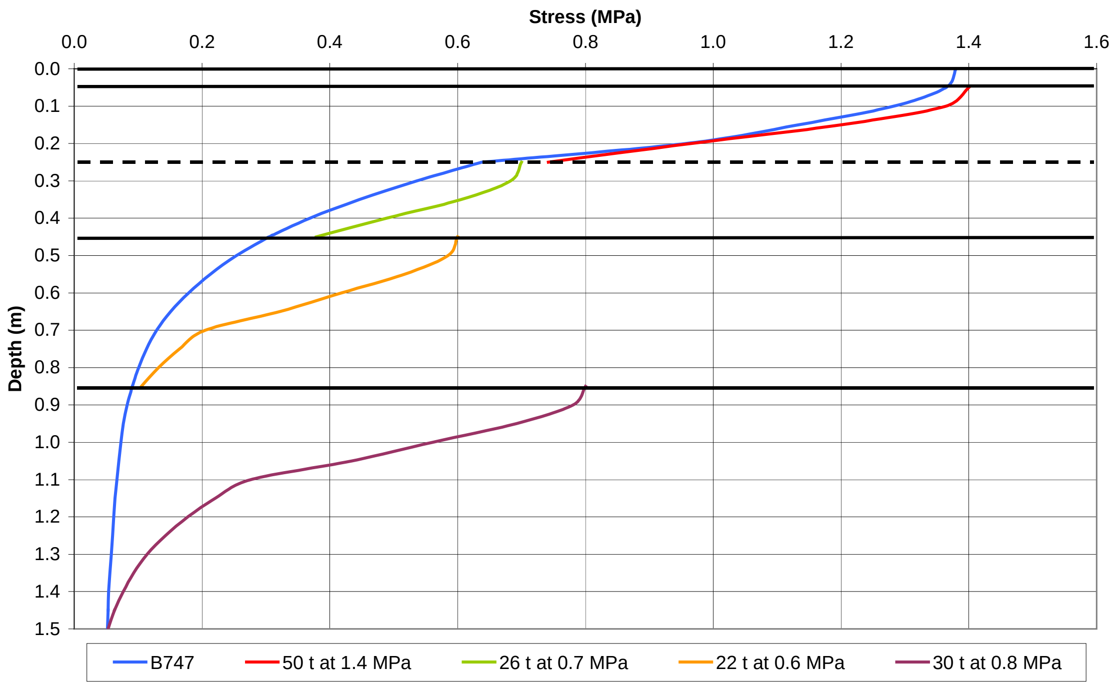

Figure 14: B747 proof rolling regime.

Figure 15: F111 proof rolling regime.

From Figure 15 it can be seen that the maximum stress induced by the Macro roller of 1.4 MPa (equal to the highest allowable tyre pressure) cannot equal the stress induced at the pavement surface by the very high tyre pressure of the F111 aircraft. However, the spreading of the stress through the asphalt surface layer is such that the roller applied to the top of the base course produces almost equal stress (1.40 MPa versus 1.46 MPa) to that induced by the aircraft from the finished surface. This inability to exceed the very high stresses induced in the upper layers by high tyre pressure military aircraft is one of the reasons for the development of the higher tyre pressure Test Rig roller. However, adequate specification and compaction of the crushed rock base course just below the asphalt is generally able to provide suitable performance without the need to fully prove the crushed rock with the higher tyre pressure roller.

Each of the materials and layers encountered during the construction of an aircraft pavement have limits to the stresses they can accommodate. Therefore, the theoretically required 0.8 MPa tyre pressure rolling of the subgrade for a B747 aircraft, may not be practical as the subgrade may fail in shear with such a high tyre pressure being placed directly on this material. In such circumstances, experience must be applied by the designer to minimise the risk of unduly failing pavements and bogging rollers. The development of the proof rolling regime should therefore take into account the following general rules:

- Sand subgrades should be covered with a layer of granular material to provide some confinement before rolling and proving.
- Clay and other weaker subgrades should be proved with lower tyre pressures to prevent shear failures under high stresses.
- Often, clay subgrades cannot be significantly improved by compaction because they are saturated and impermeable. In such cases, proving provides a check for weak spots only and pavements are designed to accommodate the poor subgrade conditions.

9 CONCLUSIONS

Proof rolling remains an important aspect of heavy duty aircraft pavement construction. Determination of suitable proof rolling regimes should be the responsibility of pavement designers. In the past, simple equations (based on single point loads and single elastic layers) and standard plots of stress with depth were utilised for proof loading regime design. Practitioners hoped that these simplifications were appropriate. With the availability of stress, strain and deflection at any position and depth in the pavement, more rigorous analysis is possible and has indicated the suitability of the traditional assumptions for many practical design scenarios.

When compared to strain and deflection, stress is the simplest damage indicator to understand and the most consistent. Stress is therefore the preferred indicator of damage for proof rolling regime design. Whilst APSDS allows specific pavement materials to be modelled, comparison of a number of scenarios has shown that the adoption of a single material on any particular subgrade can adequately represent any pavement being analysed. A pavement of 1000 mm of crushed rock on CBR 6 subgrade is recommended as standard, as this is typical for many Australian design scenarios. The traditional Boussinesq generated stress charts are also suitable, as long as the same stress generation method is used for both the roller and the aircraft being compared.

Regimes are readily able to be developed for proof rolling pavements by comparing the calculated stresses induced by the aircraft and those calculated for the proof rolling device for a number of tyre pressure and mass combinations. Roller configurations that provide modelled stresses just exceeding the aircraft induced stresses should be selected. Where a thick pavement course cannot be rolled to exceed the aircraft induced stresses, rolling the course in two layers may be required.

In practice, proof rolling regimes must take into account the site constraints. The rollers are large and expensive to transport and therefore the selection of a roller must take this into consideration. Also, clays and sands require special consideration and their proof rolling regimes should be determined by the methods described in this paper and then checked by experienced personnel and modified as required.

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