AN ASSESSMENT OF THE B-747'S CAPABILITY TO OPERATE ON ROUGH SURFACES

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FOREWORD

This report was prepared by Mr. Elijah W. Turner and Mr. John T. Riechers, Aerospace Engineers in the Loads and Criteria Group, Structural Integrity Branch, Structures Division, Flight Dynamics Directorate, Wright Laboratory at Wright-Patterson AFB OH. The work described herein is a part of the Air Force Systems Command program to determine the effect of operating aircraft from runways that have been bomb damaged and repaired. The work was conducted under Project 20545001. The Rapid Runway Repair program is managed by Air Force Engineering Support Center (AFESC/RDCR) at Tyndall AFB FL. The HAVE BOUNCE program is managed by Aeronautical Systems Divisions (ASD/TAO) at Wright-Patterson AFB. The HAVE BOUNCE Technical Manager is Mr. John T. Riechers, WL/FIBEB.

This report covers work done from May 1981 through September 1985. This manuscript was released by the authors in May 1992 for publication as a WL Technical Memorandum.

This report has been reviewed and approved.

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ABSTRACT

A study has been conducted to determine the capability of the Boeing 747 to operate on rough runways; specifically, runways that have been damaged by bombing and repaired rapidly using current Air Force procedures. The quality of the repairs has been determined that will allow the aircraft to operate from the repaired surface without being subjected to loads on the landing gears that exceed design limit load.

This study indicates that the B-747 is capable of taking off on a repaired runway at 836,000 lbs gross weight provided that repairs in the first 500 feet of the takeoff roll are at least class B. Repairs further down the runway only need to be class E. If the aircraft will traverse two repairs, tables are provided that give the minimum spacing between repairs. Consideration is not given to traversing more than two repairs.

Analysis indicates that the ability of the nose gear to withstand loads produced by traversing repair profiles can be significantly improved by increasing the precharge pressure in the shock strut. A nose gear precharge of 185 psi will reduce the peak loads sufficiently to permit a class C repair to be at any position on the runway, including the first 500 feet. Increasing the precharge pressure to 272 psi will permit class E repairs to be located anywhere.

At the maximum landing gross weight of 666000 lbs, none of the repairs A through E produced loads that exceeded design limit load during taxi at any speed. The landing touchdown, however, was not considered in this study. Until such time as an analysis becomes available, it should be considered that no repairs can be located in the touchdown area.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. ANALYSIS</td>
<td>2</td>
</tr>
<tr>
<td>2.1 General Arrangement of B-747</td>
<td>2</td>
</tr>
<tr>
<td>2.2 Repair Profiles</td>
<td>2</td>
</tr>
<tr>
<td>2.3 Computer Program</td>
<td>2</td>
</tr>
<tr>
<td>2.4 Simulations</td>
<td>4</td>
</tr>
<tr>
<td>2.5 Basis for Interpreting Results</td>
<td>5</td>
</tr>
<tr>
<td>2.6 Acceleration for Takeoff</td>
<td>5</td>
</tr>
<tr>
<td>2.7 Analysis by the Boeing Company</td>
<td>6</td>
</tr>
<tr>
<td>2.8 Landing Analysis by the Boeing Company</td>
<td>6</td>
</tr>
<tr>
<td>2.9 Load Stroke Curve</td>
<td>7</td>
</tr>
<tr>
<td>2.10 Effects of Structural Flexibility and Aerodynamic Loads</td>
<td>7</td>
</tr>
<tr>
<td>2.11 Rigid Body Damping</td>
<td>7</td>
</tr>
<tr>
<td>3. Results</td>
<td>9</td>
</tr>
<tr>
<td>3.1 Velocity Analysis</td>
<td>9</td>
</tr>
<tr>
<td>3.2 Time History Analysis</td>
<td>9</td>
</tr>
<tr>
<td>3.3 High Pressure Strut Analysis</td>
<td>9</td>
</tr>
<tr>
<td>3.4 One-Minus-Cosine Analysis</td>
<td>9</td>
</tr>
<tr>
<td>3.5 Aircraft Traversing Multiple Repair Profiles</td>
<td>10</td>
</tr>
<tr>
<td>4. Conclusions</td>
<td>11</td>
</tr>
<tr>
<td>5. Recommendations</td>
<td>12</td>
</tr>
<tr>
<td>6. References</td>
<td>13</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B-747 Design Limit Load</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Results of Boeing Company Analysis</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Critical Taxi Conditions for Single Bump Encounter</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Minimum Spacing in Feet for Traversing Two Repair Profiles</td>
<td>72</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>External Dimensions of B-747</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Nose Landing Gear Configuration</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Wing Landing Gear Configuration</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Body Landing Gear Configuration</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Landing Gear Footprint</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Bomb Damage Repair Profiles</td>
<td>19</td>
</tr>
<tr>
<td>7a</td>
<td>Reverse Thrust vs Speed</td>
<td>20</td>
</tr>
<tr>
<td>7b</td>
<td>Takeoff Velocity Time History</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Velocity Plot—Comparison of Boeing and FDL Analysis</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Nose Gear Load vs Time—Comparison of Boeing and FDL Analysis</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Wing Gear Load vs Time—Comparison of Boeing and FDL Analysis</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Body Gear Load vs Time—Comparison of Boeing and FDL Analysis</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>Effects of Upheaval on Landing Sink Rate</td>
<td>26</td>
</tr>
<tr>
<td>13</td>
<td>Nose Gear Load Stroke Curve</td>
<td>27</td>
</tr>
<tr>
<td>14</td>
<td>Wing Gear Load Stroke Curve</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>Body Gear Load Stroke Curve</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>Effect of Flexibility and Aerodynamics on Nose Gear Load</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>Effect of Flexibility and Aerodynamics on Wing Gear Load</td>
<td>31</td>
</tr>
<tr>
<td>18</td>
<td>Effect of Flexibility and Aerodynamics on Body Gear Load</td>
<td>32</td>
</tr>
<tr>
<td>19</td>
<td>Effect of Rigid Body Damping on Nose Gear Load</td>
<td>33</td>
</tr>
<tr>
<td>20</td>
<td>Effect of Rigid Body Damping on Wing Gear Load</td>
<td>34</td>
</tr>
<tr>
<td>Page</td>
<td>Title</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Effect of Rigid Body Damping on Body Gear Load</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Velocity Analysis-Free Roll Over Class A Repair at 836000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Velocity Analysis-Free Roll Over Class B Repair at 836000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Velocity Analysis-Free Roll Over Class C Repair at 836000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Velocity Analysis-Free Roll Over Class E Repair at 836000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Velocity Analysis-Reverse Thrust Braked Roll Over Class A Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Velocity Analysis-Reverse Thrust Braked Roll Over Class B Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Velocity Analysis-Reverse Thrust Braked Roll Over Class C Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Velocity Analysis-Reverse Thrust Braked Roll Over Class E Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Velocity Analysis-Braked Roll Over Class A Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Velocity Analysis-Braked Roll Over Class B Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Velocity Analysis-Braked Roll Over Class C Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Velocity Analysis-Braked Roll Over Class E Repair at 666000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Nose Gear Load vs Time-Free Roll Over Class A Repair at 836000 lbs GW and Critical Velocity</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Wing Gear Load vs Time-Free Roll Over Class A Repair at 836000 lbs GW and Critical Velocity</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Body Gear Load vs Time-Free Roll Over Class A Repair at 836000 lbs GW and Critical Velocity</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Nose Gear Load vs Time-Free Roll Over Class B Repair at 836000 lbs GW and Critical Velocity</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Wing Gear Load vs Time-Free Roll Over Class B Repair at 836000 lbs GW and Critical Velocity</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS (Cont.)

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Body Gear Load vs Time-Free Roll Over Class B Repair at 836000 lbs GW and Critical Velocity</td>
<td>54</td>
</tr>
<tr>
<td>40</td>
<td>Nose Gear Load vs Time-Free Roll Over Class C Repair at 836000 lbs GW and Critical Velocity</td>
<td>55</td>
</tr>
<tr>
<td>41</td>
<td>Wing Gear Load vs Time-Free Roll Over Class C Repair at 836000 lbs GW and Critical Velocity</td>
<td>56</td>
</tr>
<tr>
<td>42</td>
<td>Body Gear Load vs Time-Free Roll Over Class C Repair at 836000 lbs GW and Critical Velocity</td>
<td>57</td>
</tr>
<tr>
<td>43</td>
<td>Nose Gear Load vs Time-Reverse Thrust Braked Roll Over Class A Repair at 666000 lbs and Critical Velocity</td>
<td>58</td>
</tr>
<tr>
<td>44</td>
<td>Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class A Repair at 666000 lbs and Critical Velocity</td>
<td>59</td>
</tr>
<tr>
<td>45</td>
<td>Body Gear Load vs Time-Reverse Thrust Braked Roll Over Class A Repair at 666000 lbs and Critical Velocity</td>
<td>60</td>
</tr>
<tr>
<td>46</td>
<td>Nose Gear Load vs Time-Reverse Thrust Braked Roll Over Class B Repair at 666000 lbs and Critical Velocity</td>
<td>61</td>
</tr>
<tr>
<td>47</td>
<td>Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class B Repair at 666000 lbs and Critical Velocity</td>
<td>62</td>
</tr>
<tr>
<td>48</td>
<td>Body Gear Load vs Time-Reverse Thrust Braked Roll Over Class B Repair at 666000 lbs and Critical Velocity</td>
<td>63</td>
</tr>
<tr>
<td>49</td>
<td>Nose Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at 666000 lbs and Critical Velocity</td>
<td>64</td>
</tr>
<tr>
<td>50</td>
<td>Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at 666000 lbs and Critical Velocity</td>
<td>65</td>
</tr>
<tr>
<td>51</td>
<td>Body Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at 666000 lbs and Critical Velocity</td>
<td>66</td>
</tr>
<tr>
<td>52</td>
<td>Effect of Strut Pressure on Maximum Nose Gear Load for Taxi over Class E repair and 836000 lbs GW</td>
<td>67</td>
</tr>
<tr>
<td>53</td>
<td>Velocity Analysis-Free Roll Over One-Minus-Cosine at 836000 lbs GW</td>
<td>68</td>
</tr>
<tr>
<td>54</td>
<td>Nose Gear Load vs Time-Free Roll Over One-Minus-Cosine at 836000 lbs GW</td>
<td>69</td>
</tr>
<tr>
<td>FIGURE</td>
<td>DESCRIPTION</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>55</td>
<td>Wing Gear Load vs Time-Free Roll Over One-Minus-Cosine at 836000 lbs GW</td>
<td>70</td>
</tr>
<tr>
<td>56</td>
<td>Body Gear Load vs Time-Free Roll Over One-Minus-Cosine at 836000 lbs GW</td>
<td>71</td>
</tr>
<tr>
<td>57</td>
<td>Velocity Analysis : Free Roll Over A-A Repairs 60 Feet Apart at 836000 lbs GW</td>
<td>73</td>
</tr>
<tr>
<td>58</td>
<td>Velocity Analysis : Free Roll Over A-B Repairs 60 Feet Apart at 836000 lbs GW</td>
<td>74</td>
</tr>
<tr>
<td>59</td>
<td>Velocity Analysis : Free Roll Over A-C Repairs 60 Feet Apart at 836000 lbs GW</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td>Velocity Analysis : Free Roll Over A-E Repairs 400 Feet Apart at 836000 lbs GW</td>
<td>76</td>
</tr>
<tr>
<td>61</td>
<td>Velocity Analysis : Free Roll Over B-A Repairs 60 Feet Apart at 836000 lbs GW</td>
<td>77</td>
</tr>
<tr>
<td>62</td>
<td>Velocity Analysis : Free Roll Over B-B Repairs 400 Feet Apart at 836000 lbs GW</td>
<td>78</td>
</tr>
<tr>
<td>63</td>
<td>Velocity Analysis : Free Roll Over B-C Repairs 400 Feet Apart at 836000 lbs GW</td>
<td>79</td>
</tr>
<tr>
<td>64</td>
<td>Velocity Analysis : Free Roll Over B-E Repairs 400 Feet Apart at 836000 lbs GW</td>
<td>80</td>
</tr>
<tr>
<td>65</td>
<td>Velocity Analysis : Free Roll Over C-A Repairs 40 Feet Apart at 836000 lbs GW</td>
<td>81</td>
</tr>
<tr>
<td>66</td>
<td>Velocity Analysis : Free Roll Over C-B Repairs 200 Feet Apart at 836000 lbs GW</td>
<td>82</td>
</tr>
<tr>
<td>67</td>
<td>Velocity Analysis : Free Roll Over C-C Repairs 200 Feet Apart at 836000 lbs GW</td>
<td>83</td>
</tr>
<tr>
<td>68</td>
<td>Velocity Analysis : Free Roll Over C-E Repairs 500 Feet Apart at 836000 lbs GW</td>
<td>84</td>
</tr>
<tr>
<td>69</td>
<td>Velocity Analysis : Free Roll Over E-A Repairs 100 Feet Apart at 836000 lbs GW</td>
<td>85</td>
</tr>
<tr>
<td>70</td>
<td>Velocity Analysis : Free Roll Over E-B Repairs 400 Feet Apart at 836000 lbs GW</td>
<td>86</td>
</tr>
<tr>
<td>FIGURE</td>
<td>DESCRIPTION</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>71</td>
<td>Velocity Analysis: Free Roll Over E-C Repairs</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>400 Feet Apart at 836000 lbs GW</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>Velocity Analysis: Free Roll Over E-E Repairs</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>500 Feet Apart at 836000 lbs GW</td>
<td></td>
</tr>
</tbody>
</table>
1. INTRODUCTION

The US Air Force is concerned with the ability to use runways in as short a time as possible after they are bomb damaged. The Air Force Engineering Support Center (AFESC) located at Tyndall AFB FL. is in charge of developing methods for rapidly repairing runways and taxiways. The project, RAPID RUNWAY REPAIR (RRR), involves present and future methods for repairing runways and defining the quality of repairs needed for safe aircraft operations. The quality which is required is aircraft dependent. Fighter aircraft, in general, require smoother repairs than transport or bomber aircraft.

The Aeronautical Systems Division (ASD) and Wright Laboratory (WL) are assisting AFESC by providing validated computer programs which simulate aircraft operations on repaired, bomb damaged runways. The computer programs for particular aircraft are developed through contracts, or in-house efforts at WL. This project is called HAVE BOUNCE. The program is managed at ASD and WL is providing technical support. Headquarters USAF has selected a variety of fighter and transport aircraft to be evaluated.

The approach is to develop a mathematical model of each aircraft and simulate the aircraft traversing discrete runway roughness profiles. The computer programs must have the capability of predicting loads at critical locations on the aircraft. WL has monitored the technical aspects of the contractor's programs and performed some simulations in-house using a WL developed computer program called TAXI.

Some of the selected aircraft have been tested at the Air Force Flight Test Center (AFFTC) at Edwards AFB CA. These test have been compared to the computer simulations which have permitted the mathematical model to be corrected and validated, thus providing increased confidence in the accuracy of the simulations. There are no plans to test the B-747 aircraft, hence only analytical tools will be available for developing surface roughness criteria for bomb damage repair. The Boeing Company has performed some simulations of the B-747 taxiing over discrete repair profiles. These were compared to simulations produced at the WL and are presented in this report. The comparison has provided a level of confidence in the Boeing and WL simulations. It is not known if AFESC will utilize the program developed at WL to develop final repair roughness criteria or contract for a more detailed computer program to be developed.
2. ANALYSIS

2.1 General Arrangement Of B-747

The 747 family of aircraft consists of seven models, six of which are included in the Civil Reserve Air Force (CRAF). The B-747-200F is certified to a maximum gross weight of 836000 lbs and is the most critical aircraft for rough runway operations. The maximum landing weight of this aircraft is 666000 lbs. This report is directed to determining the capabilities of these two configurations of the B-747-200F. Figure 1 presents two views of the B-747 aircraft.

The landing gear system consists of five single-stage, vertical-post shock struts with oleo-pneumatic shock absorbing characteristics. The nose gear, shown in Figure 2, is a single axle, dual wheel arrangement. The main landing gear systems as shown in Figures 3 and 4 respectively. They have two posts on the wings and two on the body. Each main gear post has a bogie arrangement with twin tandem axles. The landing gear footprint is shown in Figure 5.

2.2 Repair Profiles

The procedure for repairing bomb damage to runways consists of filling the crater to within 24 inches of the surface with material discharged from the crater and compacting with heavy equipment. The remaining 24 inches is filled with crushed limestone and compacted with vibratory compactors. The surface is filled, compacted and graded to a specified degree of flatness. The entire area of the damage is then covered with articulated aluminum planks that are 1 1/2 inches thick, 24 inches wide and 6 or 12 feet long. Planks of triangular cross section 2 foot wide are used as ramps to get the aircraft on and off of the mat. The planks are joined along the long side to form an assembly which is nominally 54 by 78 feet. The AM-2 mat, as it is called, can be assembled to the side of the crater while the crater is being filled and compacted. The mat can then be pulled over the compacted crater by a tractor to complete the repair.

In order to investigate a realistic variety of repairs, 4 repair profiles have been selected. They are referred to as SINGLE BUMP, DOUBLE BUMP, SINGLE MAT and SEVERE BUMP WITH SETTLING. These configurations are presented in Figure 6.

2.3 Computer Program

A digital computer program developed in-house at the Flight Dynamics Directorate was used in the analysis. Computer program TAXI was used to simulate the B-747 traversing discrete profiles
and produced nose, wing and body gear loads as a function of time. Options are available within the program to cycle through a number of time history solutions recording only the maximum value of each solution. Use of this option provided aircraft response in the velocity domain.

For the condition of free roll, thrust is equal to the sum of aerodynamic drag and rolling friction on the runway. This is slightly conservative, because there would normally be some thrust on the engine and engine thrust creates a nose up pitching moment. Therefore, to neglect it increases the loads on the nose gear. For the condition of braking with reverse thrust, the moment due to forward thrust is zero, but the contribution due to reverse thrust is considered. This is consistent with the real situation.

The aircraft structure was modeled with 18 flexible modes of vibration, together with rigid body pitch and vertical translation. Structural damping was assumed to be 3 percent of critical damping. Lift and moment aerodynamic loads were modeled as a function of the angle of attack and aerodynamic drag was modeled using a 0.055 drag coefficient. Damping was added to rigid body pitch and vertical translation modes to obtain realistic amplitude decay rates over time periods of 5 to 10 seconds. The rigid body damping simulates aerodynamic and tire damping that were not explicitly modeled.

The landing gear shock struts were modeled to include bearing friction, hydraulic forces due to discharge of oil through an orifice and pneumatic forces from a nitrogen charged strut. Bearing friction was modeled as a force opposing the direction of stroke of the strut. The magnitude of the force was equal to the smaller of 0.1 times the bearing normal force, or the unbalance force on the strut relative to static equilibrium. Modeling in this way allows the strut to stop momentarily when it reverses direction and not begin moving again until the unbalance force exceeds a static friction of 0.2 times the normal bearing force. The pneumatic force within the cylinder was modeled as a reversible isothermal compression. The hydraulic force was modeled using a hydraulic discharge coefficient in conjunction with a variable orifice area. The orifice area is controlled by the position of the shock strut by means of a contoured metering pen that passes through the center of the orifice.

The tires were modeled using parabolic springs and drag components due to rolling friction that were assumed to act at the axle. The drag components were 0.05 times the normal force in the tire. When braking conditions were simulated, the magnitude of the drag force was assumed to have an additional component for the wing and body gears equal to 0.45 times the normal strut force. The reverse thrust resulting from all four engines was assumed to be a vector located 70.8 inches below the center of gravity of the aircraft. This results in a nose down pitching moment which creates additional load on the nose gear. The magnitude of the
reverse thrust is a function of the aircraft forward velocity. Tabular data was obtained from the Boeing Company and two parabolic curves were fitted to the data to produce the reverse thrust versus velocity presented in Figure 7a.

Specific items that were not modeled in the computer program TAXI and for which no allowance has been made include the following:

- Hydraulic damper which arrests the pitch of the articulating trucks on each of the main and wing gears
- The effect of wing lift spoilers
- The action of the wheel anti-skid mechanisms
- The effects of cylinder expansion and oil compressibility

### 2.4 Simulations

The heavy gross weight of 836000 lbs was analyzed for free roll over various profiles. This weight is larger than the maximum landing weight. Therefore, the aircraft should not be subjected to significant braking loads at this gross weight except under the emergency condition of an aborted take-off. Since use of the CRAF aircraft over repaired bomb damaged runways is an unlikely event, it is not reasonable to consider this event to occur in conjunction with another unlikely event, an aborted takeoff. Therefore, braking at 836000 lbs gross weight was not analyzed.

The maximum landing weight of 666000 lbs was analyzed for those conditions likely to occur on a normal rollout after landing. The application of brakes produces a nose down pitching moment and tends to increase nose gear loads. Reverse thrust also tends to increase nose gear loads. Although the application of heavy braking and reverse thrust is not normal operation, it is reasonably possible that they both may be required on a short runway. Therefore, this condition was analyzed.

The condition of an aircraft landing on a repair profile was not analyzed because it is not within the capabilities of the computer program TAXI.

In this investigation, there were three types of analysis performed. Each involved taxi over all 4 repair profiles at constant speed. The analyses are:

- **FREE ROLL:** Rolling friction equal to 0.05 times aircraft weight.
BRAKED ROLL: Rolling friction on the nose gear and braking friction on each of the main gears equal to 0.50 times the normal gear force.

BRAKING WITH REVERSE THRUST: Reverse thrust as a function of aircraft velocity acting along the engine axis combined with braking the same as in the braked roll.

The results of these analyses are presented in two forms: velocity plots and time histories. The velocity plots present maximum parameter response as a function of aircraft velocity over the respective repair profile. These plots are useful in identifying the critical velocities for each response parameter. The time histories display how the parameter values vary with time during a traverse of a particular profile at constant velocity.

Velocity plots are presented for each analysis over each of the repair profiles. Time history plots are presented for the critical velocity identified from the velocity analysis. The parameters that were monitored include nose gear load, wing gear load and body gear load.

2.5 Basis For Interpreting Results

The Design Limit Load (DLL) for each gear in the vertical direction was considered to be the maximum allowable load for safe operation. It is probable that the strength of each gear exceeds the DLL, but this is not known. In the future, if there is a need to establish a higher capability, then additional analysis and test can be done. Such analysis and test, however, are beyond the scope of this effort. The DLL for the gears are given in Table 1.

TABLE 1

B-747 DESIGN LIMIT LOAD

<table>
<thead>
<tr>
<th>Gear Type</th>
<th>Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Gear Vertical Load</td>
<td>196700</td>
</tr>
<tr>
<td>Wing Gear Vertical Load</td>
<td>378000</td>
</tr>
<tr>
<td>Body Gear Vertical Load</td>
<td>436000</td>
</tr>
</tbody>
</table>

2.6 Acceleration For Takeoff

The recommended class of repairs that may be permitted on the Minimum Operating Strip (MOS) takes into consideration the velocity that the aircraft is likely to have at various positions on the strip during the takeoff roll. Certain repair profiles have critical velocities and it is necessary to restrict use of that quality of repair in an area that the aircraft is likely to
traverse at the critical velocity. Figure 7b gives the aircraft velocity as a function of position down the strip form the start of the takeoff roll.

2.7 Analysis By The Boeing Company

The Boeing Company of Seattle, Washington, performed an analysis to identify critical components of the aircraft. They identified the nose gear, wing and fuselage as being potentially critical. These results are presented in Table 2 in terms of design limit load. In considering the nose gear, wing and fuselage, the margin of safety for the nose gear was the lowest of the three components. It is presumed that if it is safe to taxi over a particular profile from a nose gear load standpoint, then it is safe from a wing and body load standpoint. This assumption was necessary because the computer program TAXI does not have the provision to monitor wing and body loads.

| TABLE 2 |
| RESULTS OF BOEING COMPANY ANALYSIS |
| Taxi of B-747 over Single Pump at 836000 lbs |
| Max Wing loads | 78% DLL |
| Max Fuselage Loads | 60% DLL |
| Max Inboard Nacelle Loads | 20% DLL |
| Max Outboard Nacelle Loads | 20% DLL |
| Max Nose Gear Load | 83% DLL |
| Max Wing Gear Load | 60% DLL |
| Max Body Gear Load | 49% DLL |

Results from the computer program TAXI were compared with results from the Boeing Company analysis. The maximum vertical gear loads as a function of taxi velocity are compared in Figure 8 for taxi over a double bump at a gross weight of 836000 lbs. Although none of the gear loads exceeded design limit loads, there are differences in the two analyses. For the nose gear, the analyses differ by 3 percent (Boeing lower), wing gear by 2 percent (Boeing lower) and body gear by 2 percent (Boeing higher). Figures 9, 10 and 11 present a comparison of the time histories of the nose, wing and body gear loads respectively for taxi over a double bump at 25 knots at a gross weight of 836000 lbs. At this velocity, the analysis differ by 6 percent for the nose gear (Boeing lower), wing gear by 1 percent (Boeing higher) and body gear by 1 percent (Boeing higher). These comparisons indicate a reasonable level of confidence in the two analyses.

2.8 Landing Analysis By The Boeing Company
The Boeing Company performed a landing analysis where discrete profiles were encountered during touchdown at various sink speeds. For a B-747 at 666000 lbs gross weight, landing with the main gears on a double bump at the most critical time during the touchdown, it was determined that design limit loads would be exceeded by the vertical bending loads on the fuselage at body balance station (BBS) 1900, for a sink rate of 7.2 feet per second.

Although a sink rate of 7.2 feet per second gives reasonable latitude, caution is advised. The presence of upheaval can add to the loads. Figure 12 illustrates that a 1 inch upheaval over a distance of 10 feet produces a slope that is equivalent to a sink rate of 2 feet per second when encountered at a forward velocity of 240 feet per second.

2.9 Load Stroke Curve

The pneumatic force in each strut is a function of the precharge pressure in the strut, the volume of the strut when it is fully extended and the area of the pneumatic piston in the strut. Use of parameter values taken from engineering drawings of the shock struts produced values that were slightly different for those used in the analysis by the Boeing Company. To eliminate these differences as much as possible, small changes in the precharge pressure, strut volume and piston area were made so as to achieve the best possible match to the pneumatic load stroke curve used in the Boeing analysis. Figures 13, 14 and 15 present comparisons of the load stroke curves used in the two analyses for the nose, wing and body gears respectively.

2.10 Effect Of Structural Flexibility and Aerodynamic Loads

As a check on the reasonableness of the TAXI analysis, the effects of aircraft flexibility and aerodynamic loads were considered. A time history analysis was performed in which the flexible modes of vibration were removed from the analysis. Another analysis was performed in which the aerodynamic pressure was set equal to zero so that there would be no aerodynamic forces. Figures 16, 17 and 18 present these two analyses together with a rational analysis for taxi over a single bump at 60 knots with a gross weight of 836000 lbs, for the nose, wing and body gears respectively. The effects appear to be reasonable.

2.11 Rigid Body Damping

Damping was added to the rigid body pitch and vertical translation modes in order to account for the aerodynamic and tire damping that is not modeled explicitly in the computer program TAXI. Damping added to the rigid body modes has little effect on
the initial encounter of a repair profile, but has a significant
effect on the loads from a second profile located a considerable
distance from the first and encountered when the oscillation is at
a critical phase. The objective was to add a reasonable amount of
damping so as not to severely penalize the B-747’s capability to
encounter multiple repair profiles, yet to have confidence that the
taxi analysis is under damped and thus produces higher
(conservative) loads. Comparison of the results of the Boeing
analysis and TAXI for 25 knot over a double bump indicate that they
have about the same damping upon initial bump encounter. The
Boeing analysis displayed a damping ratio of about -0.039 and TAXI
displayed a damping ratio of about -0.034 for a period of time
immediately after leaving the repair profile. It is interesting to
note that data available from the C-130 test indicated a damping
ratio of about -0.08 after mat encounter. For multiple repair
encounter, however, the damping at lower amplitudes is of
considerable importance. A Boeing computer run made to determine
initial conditions, indicated that the oscillatory component of
nose gear load decayed from 15000 lbs to 2000 lbs in 5 cycles.
TAXI analysis indicated a decay from 15000 lbs to 2000 lbs in 7
cycles. Hence, for the same low amplitude, the Boeing analysis
indicated a damping ratio of -0.06 and TAXI indicated a damping
ratio of -0.04. This provides reasonable confidence that excessive
damping has not been added to the TAXI analysis and that the
results are expected to be conservative. The effect of rigid body
damping on nose, wing and body gear loads is shown in Figures 19,
20 and 21 respectively.
3. RESULTS

3.1 Velocity Analysis

Table 3 presents a summary of results from 12 velocity analyses with respect to nose gear vertical load, the most critical structure for taxi over repair profiles. The first 12 figures following Table 3 give nose, wing and body gear loads as a function of velocity for the analyses summarized in Table 3. Two gross weights were analyzed and 4 repair profiles. For 836000 lbs gross weight, only free roll was analyzed. For 666000 lbs gross weight, only braking was analyzed, however, it was considered both with and without thrust reversal. For those conditions where the nose gear load exceeded design limit load, the condition was reanalyzed using a nose gear strut precharge pressure adequate to reduce the loads to below design limit load.

3.2 Time History Analysis

Table 3 also identifies the particular velocity which produced the maximum nose gear load, referred to as the critical velocity. For the 836000 lbs gross weight conditions, time histories are presented for taxi over each repair profile at the critical velocity, except for conditions where the nose gear precharge pressure was increased. For the 666000 lbs gross weight conditions, time histories are presented for taxi over each repair profile at the critical velocities for combined braking and thrust reversal, which were determined to be more critical than without thrust reversal.

3.3 High Pressure Strut Analysis

For taxi at 836000 lbs, class E repairs produced nose gear loads that exceed design limit load. For this condition, a variety of computer runs were made in which the nose gear precharge pressure was increased. The results of these analyses are presented in Figure 52, which indicates that a precharge pressure of 280 psi would permit the aircraft to taxi over class E repairs at any speed.

3.4 One-Minus-Cosine Profile Analysis

Although a One-Minus-Cosine profile is not considered a likely shape for a bomb damage repair profile, this shape was analyzed because it is a smooth shape that is often used in analytical comparisons. Figure 53 presents the results of a velocity analysis for an 836000 lb aircraft traversing a 3 inch high One-Minus-Cosine shaped profile with a wave length of 60 feet. Nose, wing and body gear vertical loads are presented in figure 54, 55 and 56.
respectively, for traverse of the same profile at 60 knots, which is very near the critical velocity for the nose gear load.

3.5 Aircraft Traversing Multiple Repair Profiles

An aircraft traversing more than one repair profile may experience increased load if the second profile is encountered while the aircraft is at an unfavorable phase of the rigid body oscillation that resulted from the first profile. An analysis was performed to determine the minimum spacing between repair profiles if two are encountered. The spacing allows the rigid body oscillations to be attenuated so that the gear loads from the second profile do not exceed design limit. The results are summarized in Table 4. Figures 57 through 72 present velocity analysis plots of all possible pairs of the four repair profiles that were investigated. The case of encountering more than 2 profiles has so many possible combinations and spacings that it was not addressed in this analysis.
4. CONCLUSION

1. Aircraft velocity can be determined as a function of the distance traveled during the takeoff roll from Figure 7b for the B-747 at 836000 lbs gross weight. This chart can be used to determine the probable speed that an aircraft will encounter a repair profile, if the position of the repair profile is known relative to the start of the takeoff roll.

2. The maximum nose, wing and body gear loads can be determined for the B-747 traversing class A, B, C or E repair profiles at any speed up to takeoff speed for gross weights of 836000 and 666000 from velocity analysis plots provided in this report.

3. The minimum spacing between repair profiles is presented for pairs of class A, B, C and E repair profiles such that design limit load will not be exceeded for 836000 lbs gross weight.

4. The computer program TAXI, which was utilized in producing the results for this report, produced results that were similar to results produced by a computer program that was developed at the Boeing Company.

   a. For the nose gear, the maximum values from a time history analyses differ by 3 percent (Boeing lower), wing gear by 2 percent (Boeing lower) and the body gear by 2 percent (Boeing higher).

   b. Over a double bump at 25 knots at a gross weight of 836000 lbs, the maximum value from the time history analysis for the nose gear differed by 6 percent (Boeing lower), wing gear by 1 percent (Boeing higher) and body gear by 1 percent (Boeing higher).

   c. There was a very close correlation between the Boeing Company and TAXI analyses on the stroke curves.
5. RECOMMENDATIONS

1. It appears that the B-747 has significant capability to negotiate rough runways. If it is considered likely that it will be used in this manner, then it is recommended that a flight test program be initiated to validate or refine the roughness criteria set forth in this document.

2. Following validation of the computer model, it is recommended that a more extensive analysis be conducted to define the capability to operate over multiple repair profiles.

3. If enhancement of the B-747's rough runway capability is desirable, the practical aspects of the high pressure nose gear strut should be investigated.
6. REFERENCES


Figure 1  External Dimensions of B747
Figure 2  Nose Landing Gear Configuration
Figure 4  Body Landing Gear Configuration
Figure 5  Landing Gear Footprint
Figure 6 Bomb Damage Repair Profiles
Figure 7a Reverse Thrust vs Speed
Figure 7b Takeoff Velocity Time History

Take-off roll (feet)

SPEED VS DISTANCE FOR TAKE-OFF ROLL
747 at 836000 LBS, 160K LBS THRUST
Rolling Friction Mu = 0.03
C_D = 0.055    C_L = 0.615
Figure 8: Velocity Plot—Comparison of Boeing and FDL Analysis

BOEING 747 AT 666000 LBS, BRAKED ROLL
SINGLE CLASS C REPAIR (DOUBLE BUMP)
Figure 9  Nose Gear Load vs Time—Comparison of Boeing and FDL Analysis
Figure 10 Wing Gear Load vs Time—Comparison of Boeing and FDL Analysis
Figure 11 Body Gear Load vs Time Comparison of Boeing and FDL Analysis
VERTICAL LOADS:

UPHEAVAL: AT 240 FPS (142 KTS), UPHEAVAL IN 10 FEET WILL PRODUCE A 2 FPS EQUIVALENT SINK SPEED

RAMP: AT 240 FPS, AN AM-2 RAMP WILL PRODUCE AN 8 FPS EQUIVALENT SINK SPEED

AN AM-2 RAMP ON 1" OF UPHEAVAL (IN 10') WILL PRODUCE AN EQUIVALENT 10 FPS SINK SPEED WHICH IS DESIGN LIMIT FOR MOST AIRCRAFT.

THEREFORE A TOUCHDOWN SINK SPEED OR A DYNAMIC LOAD COUPLED WITH THE ABOVE COULD PRODUCE EXCESSIVE VERTICAL LOADS.

DRAG LOADS: SIMILARLY DRAG LOADS WILL BE INCREASED IN PROPORTION TO THE ANGLE OF THE RAMP OR UPHEAVAL PAVEMENT.
Figure 13 Nose Gear Load Stroke Curve
Figure 14  Wing Gear Load Stroke Curve
Figure 15  Body Gear Load Stroke Curve
Figure 16 Effect of Flexibility and Aerodynamics on Nose Gear Load
Figure 17 Effect of Flexibility and Aerodynamics on Wing Gear Load
Figure 18 Effect of Flexibility and Aerodynamics on Body Gear Load
Figure 19 Effect of Rigid Body Damping on Nose Gear Load
Figure 20  Effect of Rigid Body Damping on Wing Gear Load
Figure 21 Effect of Rigid Body Damping on Body Gear Load
### Table 3
CRITICAL TAXI CONDITIONS
FOR SINGLE BUMP ENCOUNTER

<table>
<thead>
<tr>
<th>CLASS</th>
<th>MAX NOSE LOAD</th>
<th>MAX NOSE LOAD</th>
<th>CRITICAL VELOCITY</th>
<th>TIME OF CRITICAL PRE- NG LOAD</th>
<th>GROSS WEIGHT</th>
<th>BRAKES REVERSE</th>
<th>THRUST 80000 LBS MAX</th>
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<td>LBS %DLL FPS SEC PSI LBS YES/NO</td>
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</tbody>
</table>
BOEING 747 AT 836000 LBS, FREE ROLL
SINGLE CLASS A REPAIR (SINGLE MAT)

Figure 22

Class A Repair at 83600 LBS GW

Speed KTS

Profile Length FT

Prof. ht in

Nose Gear Load

Wing Gear Load

Body Gear Load

NLG Force

MLG Force

BLG Design Limit Load

378000 LBS

WLG Design Limit Load

196700 LBS

NLG Design Limit Load

3.00

5.00

7.00

9.00

11.00

13.00

15.00

17.00

19.00

21.00

23.00

25.00

436000 LBS

BLG DESIGN LIMIT LOAD

378000 LBS

WLG DESIGN LIMIT LOAD

196700 LBS

NLG DESIGN LIMIT LOAD

0.00 20.00 40.00 60.00 80.00 100.00 120.00 140.00 160.00
BOEING 747 AT 836000 LBS, FREE ROLL
SINGLE CLASS B REPAIR (SINGLE BUMP)
BOEING 747 AT 836000 LBS, FREE ROLL
SINGLE CLASS C REPAIR (DOUBLE BUMP)

Figure 24 Velocity Analysis-Free Roll
Class C Repair at 836000 lbs
Figure 25

Velocity Analysis-Free Roll Over
Class E Repair at 836000 lbs GW

BOEING 747 AT 836000 LBS, FREE ROLL
SINGLE CLASS E REPAIR (SEVERE BUMP)

PROF HT IN
-1.00 0.00 3.00

0.00 50.00 100.00 150.00 200.00
PROFILE LENGTH FT

196700 LBS
NLG DESIGN LIMIT LOAD

WING GEAR LOAD

NOSE GEAR LOAD

BODY GEAR LOAD

436000 LBS
BLG DESIGN LIMIT LOAD

378000 LBS
WLG DESIGN LIMIT LOAD

SPEED KTS
Figure 26 Velocity Analysis - Reverse Thrust Braked Roll Over
Class A Repair at 666,000 lbs GW

BOEING 747 AT 666,000 LBS, REVERSE THRUST
SINGLE CLASS A REPAIR (SINGLE MAT)

PROFILE LENGTH FT

196,700 LBS
NLG DESIGN
LIMIT LOAD

436,000 LBS
BLG DESIGN
LIMIT LOAD

378,000 LBS
WLG DESIGN
LIMIT LOAD

NOSE GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD

SPEED KTS
Fig. 27 Velocity Analysis—Reverse Thrust Braked Roll Over Class B Repair at 666000 lbs GW
Figure 28: Velocity Analysis—Reverse Thrust Braked Roll Over
Class C Repair at 666000 Lbs Gm

BOEING 747 AT 666000 LBS, REVERSE THRUS
SINGLE CLASS C REPAIR (DOUBLE BUMP)

PROF. HT. IN

0.00 50.00 100.00 150.00 200.00 250.00

PROFILE LENGTH FT

196700 LBS
NGL DESIGN LIMIT LOAD

NOSE GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD

436000 LBS
BGL DESIGN LIMIT LOAD

378000 LBS
WLG DESIGN LIMIT LOAD

SPEED KTS
Figure 29

Velocity Analysis—Reverse Thrust Braked Roll Over

Class E Repair at 666,000 lbs GW
BOEING 747 AT 666000 LBS, BRAKED ROLL
SINGLE CLASS A REPAIR (SINGLE MAT)

Figure 30
Velocity Analysis: Braked Roll Over
Class A Repair at 666000 lbs GM

PROF. HT IN

PROFILE LENGTH FT

196700 LBS
NLG DESIGN
LIMIT LOAD

436000 LBS
BLG DESIGN
LIMIT LOAD

378000 LBS
MLG DESIGN
LIMIT LOAD

NOSE GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD

SPEED KTS
BOEING 747 AT 666000 LBS, BRAKED ROLL
SINGLE CLASS B REPAIR (SINGLE BUMP)

Figure 31: Velocity Analysis - Braked Roll Over
Class B Repair at 666000 lbs.
Figure 3.2 Velocity Analysis-Braided Roll Over

Boeing 747 at 666,000 LBS, Braided Roll
Single Class C Repair (Double Bump)

Profile Length FT

Nose Gear Load

Wing Gear Load

Body Gear Load

NLG Force at 0.00 - 100.00 lbs

MLG Force at 0.00 - 100.00 lbs

Profile Height in.

196,700 LBS NLG Design Limit Load

436,000 LBS Big Design Limit Load

378,000 LBS WLG Design Limit Load

Speed KTS
BOEING 747 AT 666000 LBS, BRAKED ROLL
SINGLE CLASS E REPAIR (SEVERE BUMP)

Figure 33
Velocity Analysis-Break Roll Over

Class E Repair at 666000 lbs GW
Figure 34  Nose Gear Load vs Time—Free Roll Over
Class A Repair at Critical Velocity
Figure 35 Wing Gear Load vs Time—Free Roll Over Class A Repair at Critical Velocity
Figure 36  Body Gear Load vs Time—Free Roll Over
Class A Repair at Critical Velocity
Figure 37 Nose Gear Load vs Time—Free Roll Over Class B Repair at Critical Velocity
Figure 38  Wing Gear Load vs Time-Free Roll Over
Class B Repair at Critical Velocity
Figure 39  Body Gear Load vs Time-Free Roll Over
Class B Repair at Critical Velocity
Figure 40: Nose Gear Load vs Time - Free Roll Over Class C Repair at Critical Velocity

B747, 836000 LBS, CLASS C REPAIR, FREE ROLL, 41 FPS
Figure 41 Wing Gear Load vs Time-Free Roll Over
Class C Repair at Critical Velocity
Figure 42 Body Gear Load vs Time-Free Roll Over
Class C Repair at Critical Velocity
Figure 43 Nose Gear Load vs Time-Reverse Thrust Braked Roll Over Class A Repair at Critical Velocity
Figure 44  Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class A Repair at Critical Velocity
Figure 45  Body Gear Load vs Time—Reverse Thrust Braked Roll Over
Class A Repair at Critical Velocity
Figure 46 Nose Gear Load vs Time—Reverse Thrust Braked Roll Over Class B Repair at Critical Velocity
Figure 47 Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class B Repair at Critical Velocity
Figure 48  Body Gear Load vs Time—Reverse Thrust Braked Roll Over Class B Repair at Critical Velocity
Figure 49 Nose Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at Critical Velocity
Figure 50
Wing Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at Critical Velocity

WING GEAR TIME HISTORY
B747, 666000 LBS, 42 FPS
CLASS C REPAIR (DOUBLE BUMP)
Figure 51  Body Gear Load vs Time-Reverse Thrust Braked Roll Over Class C Repair at Critical Velocity
Figure 5.2 Effect of Strut Pressure on Maximum Nose Gear Load

Maximum Nose Gear Load vs Precharge Pressure
B747 at 836000 lbs, Taxi-over Class E Repair
At Critical Velocity
BOEING 747 AT 836000 LBS, FREE ROLL
1-COS BUMP 60° WAVE 3" AMP

Figure 53
Velocity Analysis-Free Roll Over
One-Minus-Cosine at 836000 lbs GN
Figure 54 Nose Gear Load vs Time-Free Roll Over
One-Minus-Cosine at 836000 lbs GW
Figure 55

Wing Gear Load vs Time-Free Roll Over

One-Minus-Cosine at 836000 lbs GW

WING GEAR TIME HISTORY
B747, 836000 LBS, 60 KNOTS
3 INCH ONE-MINUS-COSINE BUMP
60 FOOT WAVE LENGTH
Figure 56 Body Gear Load vs Time-Free Roll Over One-Minus-Cosine at 836000 lbs GW
### Table 4
MINIMUM SPACING IN FEET FOR TRAVERSING TWO REPAIR PROFILES

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<th>B</th>
<th>C</th>
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<td>400</td>
<td>500</td>
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</table>

* E profile must not be traversed at speeds between 20 and 40 knots.
Figure 57  Velocity Analysis: A-A Repairs 60 Feet Apart
Figure 58: Velocity Analysis: A-B Repairs 60 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
A - B REPAIRS 60 FEET APART

PROFILE LENGTH FT

PROFILE HT IN

196200 LBS
NLG DESIGN
LIMIT LOAD

436000 LBS
BLG DESIGN
LIMIT LOAD

378000 LBS
WLG DESIGN
LIMIT LOAD

NLG FORCE
-10^3
100,000
200,000
300,000
400,000
500,000
600,000

MLG FORCE
-10^4
10,000
20,000
30,000
40,000
50,000
60,000

SPEED KTS

0.00 20.00 40.00 60.00 80.00 100.00 120.00 140.00 160.00

NOSE GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD
Figure 59: Velocity Analysis - A-C Repairs 60 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
A - C REPAIRS 60 FEET APART

PROFILE LENGTH FT

436000 LBS
BLG DESIGN
LIMIT LOAD

378000 LBS
WLG DESIGN
LIMIT LOAD

NLG FORCE 1.5 x 10^3
M.G. FORCE 3 x 10^4

196700 LBS
NLG DESIGN
LIMIT LOAD

NOSE GEAR LOAD
WING GEAR LOAD
BODY GEAR LOAD

SPEED KTS
BOEING 747 AT 836000 LBS, FREE ROLL
A - E REPAIRS 400 FT APART
Figure 61: Velocity Analysis - B-A Repairs 60 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
B - A REPAIRS 60 FEET APART

PROFILE LENGTH FT

PROF HT IN

SPEED KTS

0.00 20.00 40.00 60.00 80.00 100.00 120.00 140.00 160.00

0.00 10.00 20.00 30.00 40.00 50.00 60.00

NLG FORCE -10^3 152.00 208.00 264.00 320.00 376.00

MLG FORCE -10^4 0.00 10.00 20.00 30.00 40.00

196700 LBS
NLG DESIGN LIMIT LOAD

NOSE GEAR LOAD

436000 LBS
BLG DESIGN LIMIT LOAD

378000 LBS
WLG DESIGN LIMIT LOAD

WING GEAR LOAD

BODY GEAR LOAD
BOEING 747 AT 836000 LBS, FREE ROLL
B - B REPAIRS 400 FEET APART

Figure 62 Velocity Analysis: B-B Repairs 400 Feet Apart

- 436000 LBS
  BLG DESIGN LIMIT LOAD
- 378000 LBS
  WLG DESIGN LIMIT LOAD

196700 LBS
NLG DESIGN LIMIT LOAD

Nose Gear Load
Wing Gear Load
Body Gear Load

Profile Length FT
Speed KTS
Figure 63: Velocity Analysis: B-C Repairs 400 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
B - C REPAIRS 400 FEET APART

- NLG FORCE
  - 150,000
  - 100,000
  - 50,000
  - 10,000

- MLC FORCE
  - 30,000
  - 20,000
  - 10,000

PROFILE LENGTH FT -10

PROF HT IN

SPEED KTS

LIMIT LOAD

196700 LBS
NLG DESIGN
LIMIT LOAD

436000 LBS
BLG DESIGN
LIMIT LOAD

378000 LBS
WLG DESIGN
LIMIT LOAD

NOSE GEAR LOAD
WING GEAR LOAD
BODY GEAR LOAD
Figure 64 Velocity Analysis: B-E Repairs 400 Feet Apart

Boeing 747 at 836000 lbs, Free Roll
B - E Repairs 400 Feet Apart

NLG Force 150,000 lbs 200,000 lbs 250,000 lbs 300,000 lbs 350,000 lbs 400,000 lbs
MLG Force 100,000 lbs 150,000 lbs 200,000 lbs 250,000 lbs 300,000 lbs

Profile Height in

Profile Length FT

196700 LBS NLG Design Limit Load
Nose Gear Load
Wing Gear Load
Body Gear Load

436000 LBS MLG Design Limit Load
378000 LBS WLG Design Limit Load

SPEED KTS
Figure 65  Velocity Analysis : C-A Repairs 40 Feet Apart
BOEING 747 AT 836000 LBS, FREE ROLL
C - B REPAIRS 200 FEET APART

Figure 66 Velocity Analysis: C-B Repairs 200 Feet Apart
Figure 67 Velocity Analysis: C-C Repairs 200 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
C - C REPAIRS 200 FEET APART

PROFILE LENGTH FT

SPEED KTS
Figure 68: Velocity Analysis - C-E Repairs 500 Feet Apart

Boeing 747 at 836000 lbs, free roll
C-E repairs 500 feet apart

Profile length (ft) -10^4

Pressure height (in)

Speed (kts)

Nose gear load
Wing gear load
Body gear load

Limit load
BLG design limit load
NLG design limit load

436000 lbs
378000 lbs
Figure 69 Velocity Analysis: E-A Repairs 100 Feet Apart
Figure 70: Velocity Analysis: E-B Repairs 400 Feet Apart

BOEING 747 AT 836,000 LBS, FREE ROLL
E-B REPAIRS 400 FEET APART

PROFILE LENGTH FT

-10^3

PROFILE HT IN

-3.00

436,000 LBS
BLG DESIGN
LIMIT LOAD

378,000 LBS
WLG DESIGN
LIMIT LOAD

196,700 LBS
NLG DESIGN
LIMIT LOAD

NLG FORCE, -10^3

MLG FORCE

0.00 20.00 40.00 60.00 80.00 100.00

0.00 20.00 40.00 60.00 80.00 100.00

SPEED KTS

NOSE GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD
Figure 71 Velocity Analysis: E-C Repairs 400 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
E - C REPAIRS 400 FEET APART

PROFILE LENGTH FT -10^4

MLG FORCE -10^3

NOSG GEAR LOAD

WING GEAR LOAD

BODY GEAR LOAD

SPEED KTS

436000 LBS
BLG DESIGN
LIMIT LOAD

378000 LBS
MLG DESIGN
LIMIT LOAD

196700 LBS
MLG DESIGN
LIMIT LOAD

NLG DESIGN
LIMIT LOAD
Figure 72 Velocity Analysis: E-E Repairs 500 Feet Apart

BOEING 747 AT 836000 LBS, FREE ROLL
E - E REPAIRS 500 FEET APART

NLG FORCE: 100,000 LBS
MLG FORCE: 300,000 LBS

PROFILE LENGTH FT

SPEED KTS