Report No. UMTA-CA-06-0098-82-2

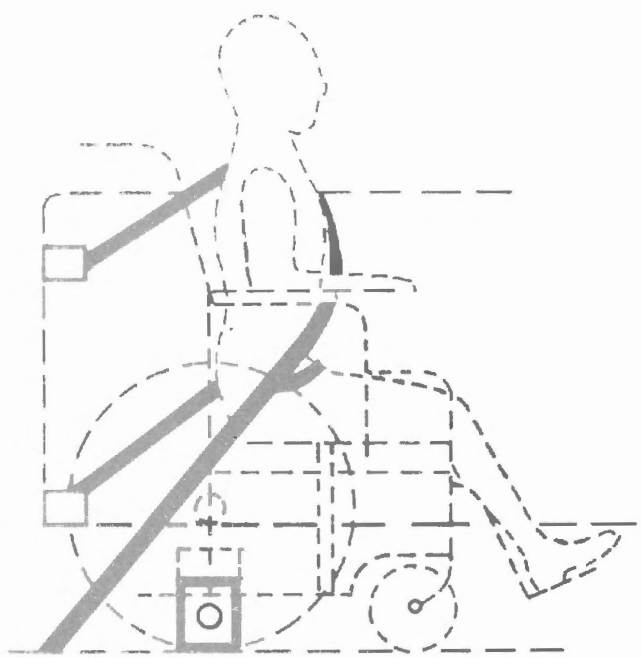
U.S. Department
of Transportation

Research and
Special Programs
Administration

Wheelchair Securement
On Bus and Paratransit Vehicles

Prepared by:
California Department
of Transportation

July 1981



Technical Assistance - an UMTA Program

The preparation of this report has been financed through a contract with the U.S. Department of Transportation, Urban Mass Transportation Administration, under the Urban Mass Transportation Act of 1964, as amended.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CA-06-0098-82-2		

4. Title and Subtitle
Wheelchair Securement on Bus and Paratransit Vehicles

5. Report Date
July 1981

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
64-120-631077

9. Performing Organization Name and Address
California Department of Transportation
P. O. Box 1499
Sacramento, CA 95807

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
CA-06-0098

12. Sponsoring Agency Name and Address
U.W. Department of Transportation
Urban Mass Transportation Administration
400 Seventh Street, S.W.
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
Covering 1980-81 tests

14. Sponsoring Agency Code

15. Supplementary Notes
This is the final report to be published under UMTA grant CA-06-0098 to study the "Aafety of Loading & Securement Hardware for Transporting Wheelchair Passengers".

16. Abstract

The performance of wheelchair securement systems is evaluated from 59 tests at various velocity and deceleration levels with a 50th percentile male dummy occupying the wheelchair. Manual and electric powered chairs were placed in forward or side facing orientations.

This report gives the results of those tests. It also discusses many of the problems associated with providing securement for wheelchairs and their users, as well as with setting up dynamic tests for securement systems and evaluating the test results.

Recommendations are made for the development and improvement of securement systems to ensure a safe and reliable mode of transportation for the confined wheelchair user.

17. Key Words	18. Distribution Statement
Wheelchair transportation, wheelchair securement, handicapped transportation, accessible transportation, wheelchair crashworthiness	Available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)　　Reproduction of completed page authorized

CALIFORNIA DEPARTMENT OF TRANSPORTATION

DIVISION OF MASS TRANSPORTATION

WHEELCHAIR SECUREMENT ON BUS AND PARATRANSIT VEHICLES

FINAL REPORT

Sacramento, California

July 1981

by

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UMTA Contract CA-06-0098

EXECUTIVE SUMMARY

This publication is a continuation of the April 1981, interim report "Wheelchair Securement on Bus and Paratransit Vehicles." The initial report published the results of 42 tests in Phases I and II. In this report, Phase III and IV results are summarized and the conclusions are drawn from all four phases of testing.

Ten wheelchair securement system tests were conducted in Phase III. The primary purpose of seven of these tests was to determine the effect of reducing the sled deceleration rate from 10 g's to 5 g's on systems that had previously failed. Four of the seven tests maintained the 20 mph speed, and the remaining three reduced the velocity to 10 mph. These velocity and deceleration reductions were needed to determine the level at which these securements would prove effective during a dynamic crash event. The remaining three tests were designed to answer questions posed by the previous series of tests.

In Phase IV, seven wheelchair securement system tests were conducted. The purpose of five of the tests was to gain more complete data on the modified, proprietary single-rim-latch and the belt-around-the-armrest restraint. The remaining two tests were to provide data on systems not previously tested. The single-rim-latch tests were run at 20 mph and 5 g's. The other tests were run at 20 mph and 10 g's.

As before, the tests simulated a frontal crash of a bus with the wheelchairs faced either in the direction of travel or perpendicular to it (side facing). The same manual and electric-powered wheelchair models were used except in the single-rim-latch test (1968) utilizing the electric wheelchair. This wheelchair had been modified; the die cast wheels, normally used on the electric powered wheelchairs, were too large to be gripped by the securement system and were replaced with spoke rim wheels. The same 50th percentile male anthropomorphic dummy (165 pounds) occupied each of the wheelchairs.

Most of the securement systems were inadequate in providing complete protection and securement to the wheelchair and user at the 20 mph/10 g's level. Depending upon the test conditions, the various tests resulted in excessive head and body movement with head or body strikes or major wheelchair damage, or both. There is a need to develop an improved securement to withstand the 20 mph/10 g's dynamic test while providing adequate user and wheelchair protection and securement.

The data showed that the velocity at impact had a greater influence on wheelchair damage and occupant injury than the rate of deceleration (in the velocity and deceleration ranges used in these tests). A 50% decrease in speed resulted in a smaller head excursion and less chair damage than a 50% decrease in deceleration. Reduction of both parameters markedly reduced impact damage on both wheelchair and occupant. The decoupling effect, described in the previous report, could be seen in the test films. In the side-facing tests, the wheelchair would lean and twist under while the dummy maintained its trajectory path. The greater weight of the electric-powered wheelchairs caused greater damage to the wheelchair and exerted higher loads on the occupant than were experienced in similar tests using manual wheelchairs.

PREFACE

This second and final report on "Wheelchair Securement on Bus and Paratransit Vehicles" is part of the Urban Mass Transportation Administration's study grant (CA-06-0098) for wheelchair securement research by the California Department of Transportation (Caltrans). The 42 tests described in interim report number 1 comprised Phase I (28 tests) and Phase II (14 tests). The 17 tests described in this report comprised Phase III (10 tests) and Phase IV (7 tests).

The report represents an ongoing study to satisfy the need for a safe, reliable and easy-to-operate wheelchair securement system. Because this is a continuation of the interim report, definitions, explanations and technicalities discussed in the first report will not be repeated.

All of the securement systems used in the Phase III series of testing were the same as those in the first two phases. Phase IV repeated two securement system types and included additional testing of two new systems, one using an unsecured wheelchair placed beside a padded panel. The wheelchairs were the same as the manual and electric-powered models used in previous tests except for one modification of the electric powered wheelchair with spoke rim wheels to accommodate the single rim latch securement. The test sled configuration represents a wheelchair station on the left side of the bus. In side-facing tests the left side of the wheelchair was nearest the forward end of the test sled.

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STUDY DESIGN

This section of the report describes the equipment used, the test procedures and the data collection methods.

Dynamic-Static-Analytical Correlation

Minicars, Inc., as part of the wheelchair securement testing contract, performed an analytical evaluation of the results of the T-bar wheelchair restraint system testing. The analysis was compared with the actual static and dynamic test results. Details of the method and results of the analytic study are presented in Appendix B.

The forward T-bar securement system was analyzed. The analysis determined the 1010 steel members of the wheelchair would collapse when subjected to loads between 1600 and 1954 pounds, depending upon the grade of 1010 steel used. Failure of the upper footrest was predicted. Static test 1045A confirmed the analysis. The footrest had an initial yield at 1300 pounds seat belt load and collapsed at 1600 pounds. The 1060 dynamic test, however, did not stress the wheelchair to a maximum load; the measured belt load was 850 pounds, which is less than the predicted minimum collapse load. Because of the limited data of test 1060, the dynamic response was inconclusive in verifying the analytic evaluation.

The analysis was based on the T-bar securement system that grips the frame of the wheelchair at two symmetrical places during a forward-facing test. All of the tests performed after receipt of the report gripped the chair in other locations, some were unsymmetrical, which would require major modifications to the computer programming. The analysis is also based on a folding wheelchair and would require extensive revision to analyze the nonfolding electric-powered wheelchairs that were used in some tests. Sidefacing tests would also require major revisions. Thus, a new analysis would be required for each securement system, electricpowered wheelchair, and side-facing orientation. Further analysis was not performed because dynamic tests were less costly, could be performed at a rate of one or two per day, and provided the information needed to complete the project.

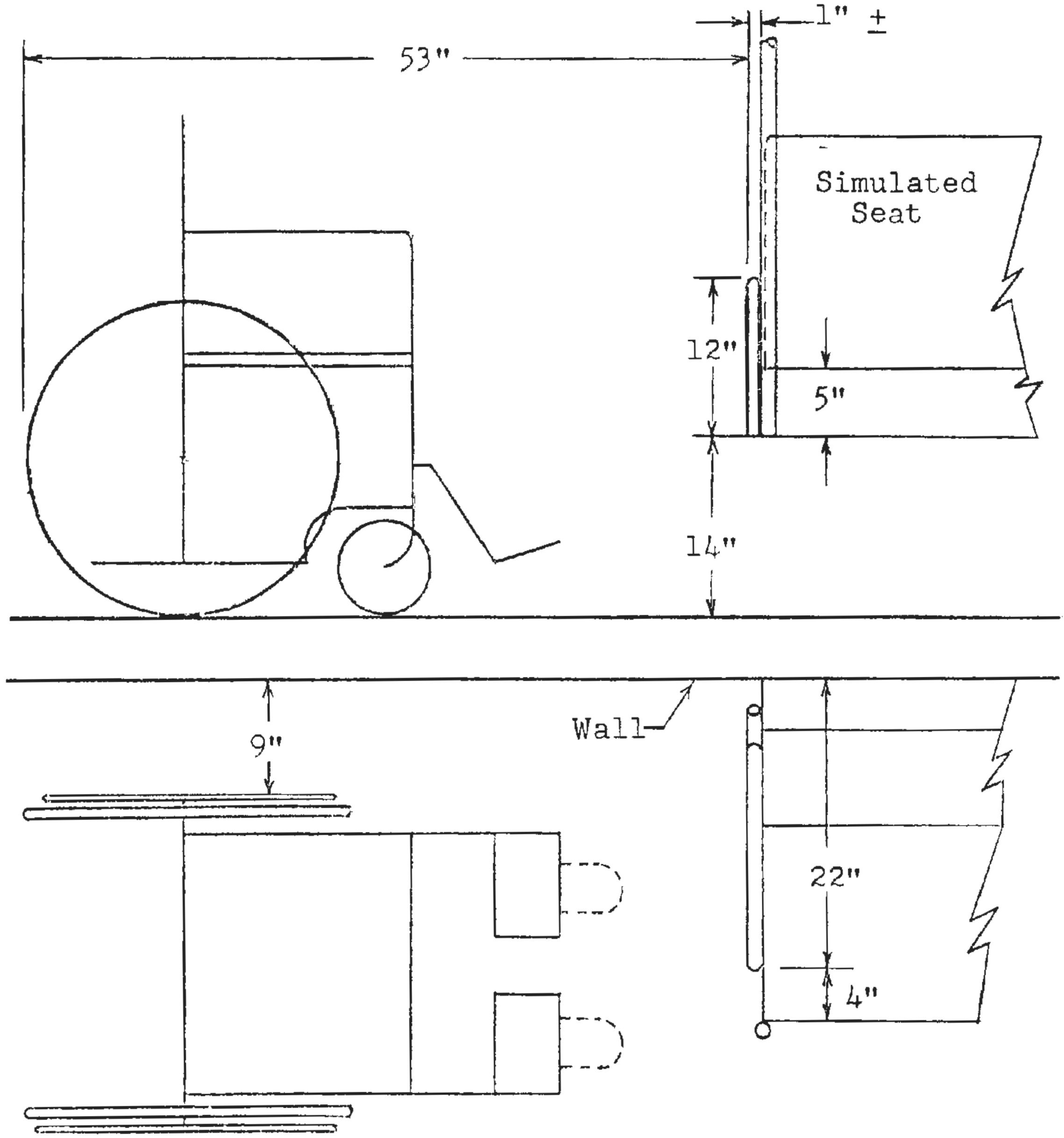
Dynamic Test Parameters

Parameters not mentioned are the same as those detailed in the interim report. The following parameters were varied for the final two phases of testing:

- Type of chair
- Chair facing direction
- Chair securement
- Sled impact speed and deceleration rate
- Wheelchair securement station envelope

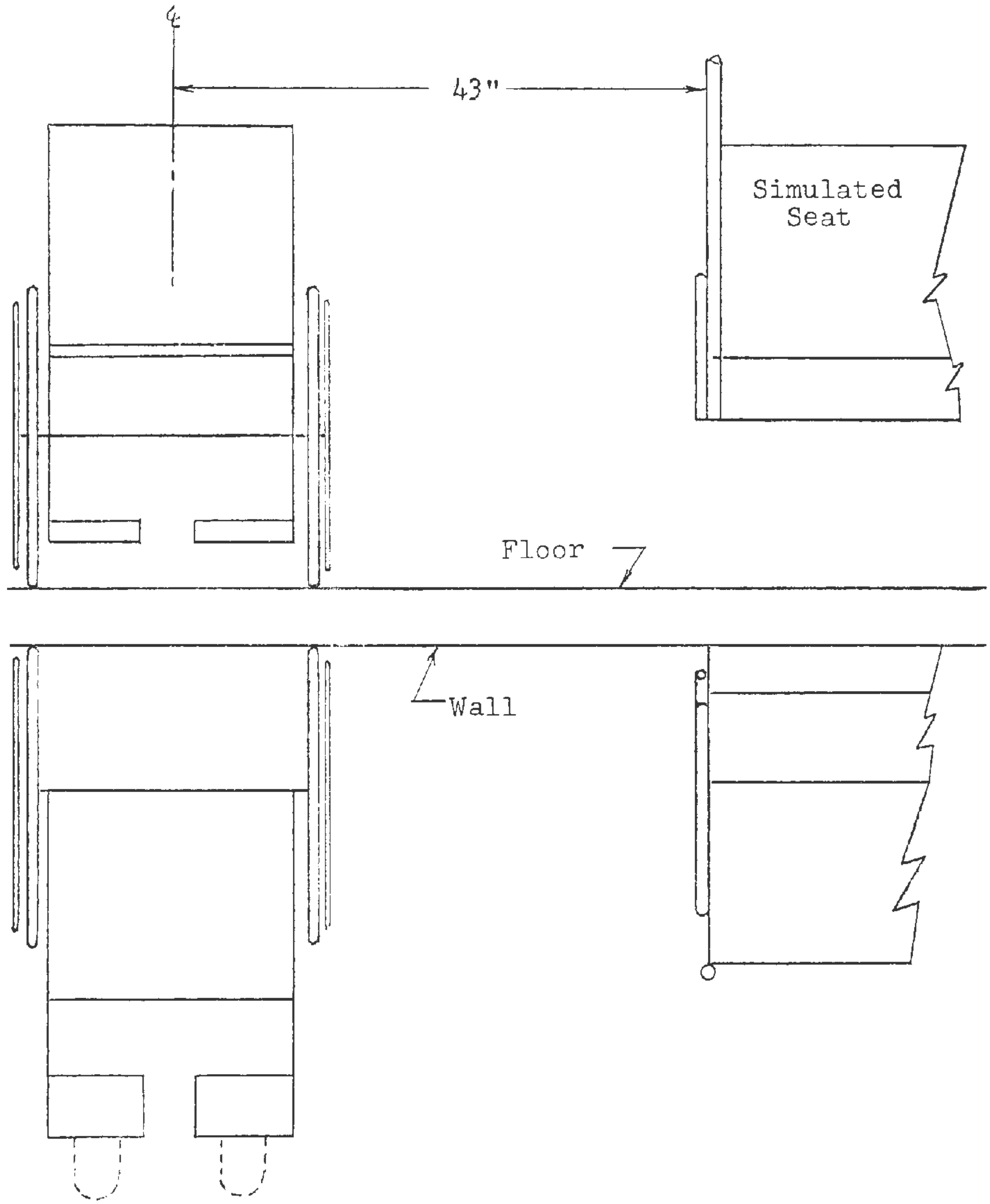
Chair Type. The same two models of Everest and Jennings wheelchairs, Model P8AUU-260-770 manual wheelchair and Model P8AU-200 32-770 electric powered wheelchair were used. Five tests, 1968, 1971, 1880, 1884, and 1887 added the electric wheelchair feature to previous securement types tested on manual wheelchairs. The single rim latch system, which attaches to the rear wheel, required the electric wheelchair to employ spoke wheels because the wide metal or plastic spoked wheels have tires and rims that are too wide to pass through the latch opening. The later model electric powered wheelchairs have the batteries completely enclosed, whereas the previously tested models had the batteries tied down with bungee cords.

Chair Facing Direction. Completing the data set for each securement type required orienting the wheelchair in a direction not tested before, either in the direction of travel or perpendicular to it. On the test sled, forward-facing wheelchairs were always positioned with the rear of the back wheels 53 inches from the armrest of the aisle-facing seat. Side-facing wheelchairs where positioned with the centerline of the chair 43 inches



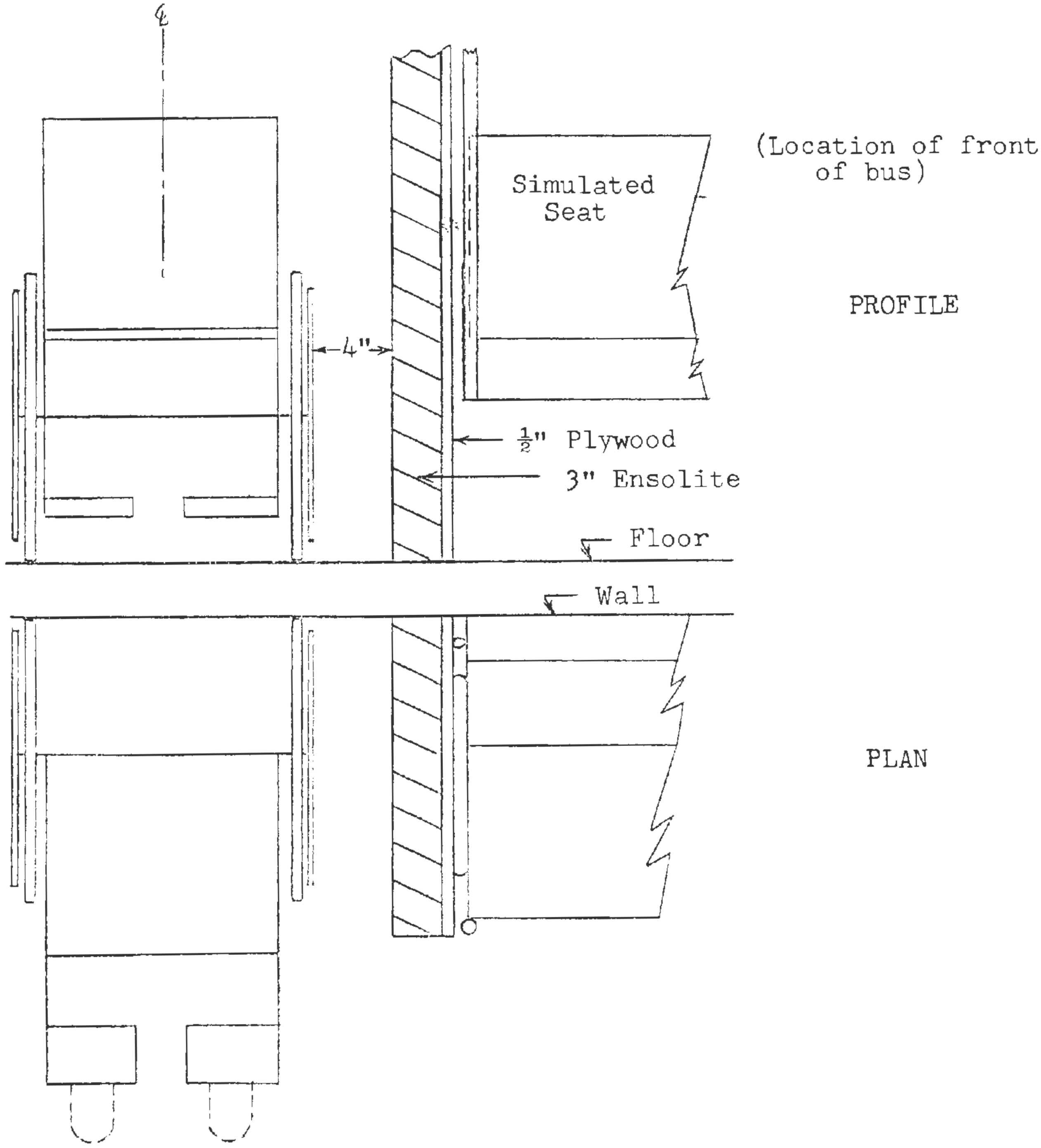
FORWARD-FACING TEST CONFIGURATION

FIGURE 1



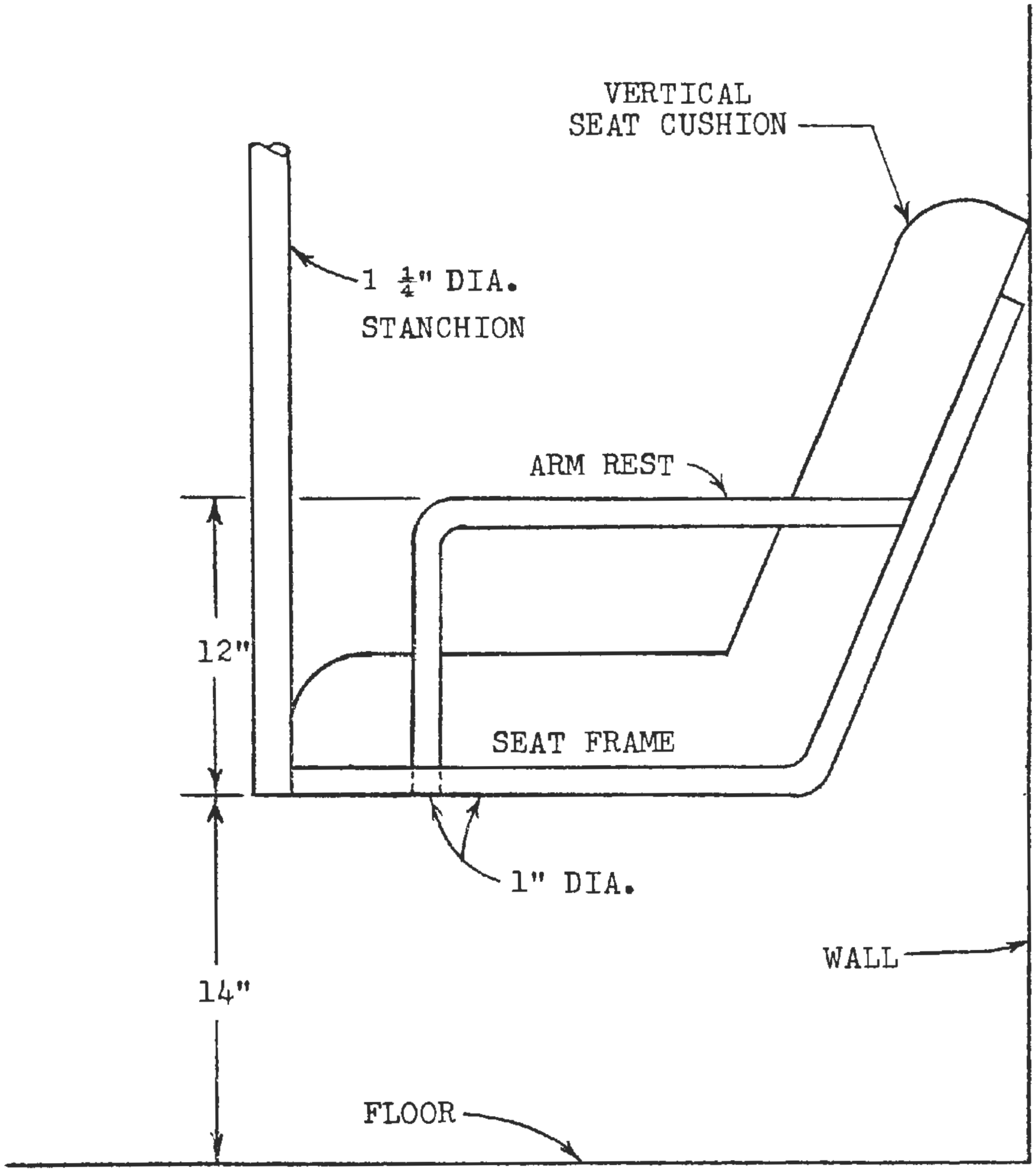
PHASE III: SIDE-FACING TEST CONFIGURATION

FIGURE 2



PHASE IV: SIDE-FACING TEST CONFIGURATION

FIGURE 3



SIMULATED BUS SEAT
FIGURE 4

from the armrest. The very last test was conducted with the wheelchair in the side-facing mode and its forward wheel four inches from a padded panel that was installed perpendicular to the simulated bus side wall. Figures 1 through 3 illustrate the wheelchair orientations, and Figure 4 shows the simulated bus seat.

Because many wheelchair users have expressed their objections to facing the other passengers in a transit vehicle, the rear-facing wheelchair orientation was not used in these 17 tests. Rear-facing securements have high head rests that block the forward view of other seated passengers and impair their ability to identify the next stop. Also, the rear-facing wheelchair users are not accustomed to determining where they are by identifying landmarks passed.

Chair Securement. Commercial wheelchair securement systems are designed to restrain the wheelchair during normal bus movements, not crash situations. Therefore, many of the tests were performed using "generic" systems that held the chair in a similar manner to that of the commercial system but with sufficient strength to prevent yielding of the securement system.

The single rim latch is one of the few systems that were used off-the-shelf. In two of the previous tests (1187 and 1196) this securement had failed to maintain attachment with the wheelchair during the dynamic crash event. Test 1197 used our modification on the system to ensure the securement would not fail during the test. Contact with the company led to the modification of the single rim latch securement system by the manufacturer. Because this proprietary securement was widely used, it was necessary to test the modified system to verify not only the soundness of the modification but also the behavior of the chair and the user in a dynamic crash event. The manufacturer modified system held firmly in all the tests.

The proprietary automatic rim pin system is secured to the floor of the bus below the forward facing seat. For the wheelchair user to employ the system, the seat must be placed in a folded position. The wheelchair should be backed into a position where the back wheels touch the raised seat. The user activates the system by pushing a button on the side of the bus. The air-propelled rim fingers extend until each back wheel is securely retained. The generic automatic rim pin used in Test 1976 copied the securement attachment in terms of how and where the rim pin holds the wheelchair but not the means of activation (air pressure).

The final test of the project used a padded vertical transverse wall at the forward end of the wheelchair station in the trajectory path of chair and dummy. The degree of wheelchair and user movement was demonstrated without any securement attachment.

Sled Speed and Deceleration at Impact. Because of the decoupling effect, Phase I and II tests indicated that sled velocity at impact had a greater effect on the wheelchair damage and occupant injury than the rate of deceleration (in the range of velocity and deceleration rates used in the tests). In order to obtain data to support or refute the foregoing, the velocity and deceleration rates were varied in the Phase III tests.

Wheelchair Securement Station Envelope. Only Phase IV's last test varied from the established wheelchair securement station envelope. The wheelchair was placed in the side-facing direction and a side panel was included four inches away from the wheelchair, as shown in Figure 3.

Data Collection and Film Records

As in the Phase I and II tests, Minicars, Inc., of Goleta, California performed the Phase III and IV testing and data analysis. High-speed movies were taken of each test. The four high-speed cameras used were located in the following positions:

1. Sled mounted overhead
2. Sled mounted side looking
3. Off-board front looking
4. Off-board side looking

An off-board side-looking Polaroid still camera took a sequence of eight photographs of each test beginning at sled impact and ending about the time the sled had come to a complete stop.

Test Setup

The dynamic tests were conducted on Minicar's Horizontal Impact Test Sled II (HITS II) and test track. The HITS II is similar to the HITS I used in Phase I testing and operates on the same principle as HITS I. The sled is propelled by compressed air and decelerated by impacting one or more metal bands, which are deformed in a controlled manner. The sled is accelerated to 10 or 20 mph, as required, and then decelerated at a rate of 5 or 10 g's, as specified. Samples of the sled's deceleration pulse can be found in the Appendix. The HITS II sled and track differ from the HITS I sled and track; the HITS II track is longer and provides greater speed and deceleration regulation, and the HITS II sled has a simulated bus wall on the left side and a simulated aisle-facing seat attached to the wall at the front of the sled.

It should be noted that the HITS I side-facing tests (Phase I) were run with the right side of the dummy toward the front of the sled; whereas, the subsequent phase II, III and IV side-facing tests were performed with the left side of the dummy toward the front.

Securement Systems Tested

Tests were conducted in two phases. Phase III tests and the first three Phase IV tests repeated Phase I and II securement system types and varied the test parameters. Phase IV tested one new securement system and a padded side panel without the aid of a securement system. A brief description of each system's performance will be discussed in the section SUMMARY OF DYNAMIC TEST RESULTS.

Head Excursion Measurement

Head excursion was judged from two camera views: the side-facing sled camera and the side-facing ground camera. The head distance could be calculated in two ways: The initial head location and final head positions were noted, and the resulting difference was the distance moved. Or the maximum location of head movement can be measured relative to the height and distance from the steel armrest. Since the dummy's initial position was known, the total distance was added or subtracted, as the case may be, from the distance of dummy to the steel armrest which gave the distance traversed.

The difficulties encountered were as follows:

1. Film distortion at the edges, especially caused by the side-facing sled camera using the wide angle lens. Because the size of the photo is such that the dummy is at the left edge of the film at the beginning of the tests and at the right edge at the maximum forward dummy movement, there was definite distortion of positions measured.

2. Sometimes the head fell out of camera view.

3. The scale, determined from existing materials and inch tape targets placed on the dummy and sled did not necessarily fall in the same reference plane as the dummy's head.

The following is an example of typical scaling. The wheelchair armrest, 10 1/2 inches in length, was used as a scaling factor. The two end points of the armrest were determined on the Vanguard motion analyzer. The actual armrest length was divided by the measured armrest length (difference between the two points) and this scaling factor was multiplied against the measured head excursion distance to determine the desired head excursion:

$$\text{Calculated head excursion} = \text{Measured head excursion} \times \frac{\text{Actual armrest length}}{\text{Measured armrest length}}$$

Because edge distortion was more inherent in the sled camera, the preferred calculated head excursion was determined using the ground camera and measuring the head relative to the steel armrest. The sled camera aided in locating head position when the ground camera shots were hard to discern or unusable. The calculations were tempered with a practical observation of the film action. For example, if the forehead struck the armrest, the distance calculated should be close to the sum of the distance between the center of the top of the dummy's head and the armrest plus the distance from the forehead to the top of the head, approximately three inches.

SUMMARY OF DYNAMIC TEST RESULTS

This section summarizes the results of tests on nine generic types of securements and one specific manufactured model. A detailed description of each of the 17 tests run, the results, and photographs are given in Appendix A.

Typical Conditions

The activity of the dummy and the damage to the wheelchairs in this group of tests were similar to those reported in the first interim report. For this velocity and deceleration range, chair damage was determined to be more dependent on sled speed than on sled deceleration (which was not the same as dummy or chair deceleration because of the decoupling effect). The likelihood of dummy strike was increased when comparing the tests at 20 mph versus the 10 mph tests. There was greater wheelchair extension and deformation and the head excursion was increased between 35% and 52% at the greater speed. At the same velocity level, a reduction in deceleration from 10 g's to 5 g's resulted in a 4 to 20 percent reduction in head excursion, but the wheelchair still suffered approximately the same degree of damage. The HIC, CSI and user belt load did not differ consistently from the results of the regular crash pulse test at 20 mph/10 g's.

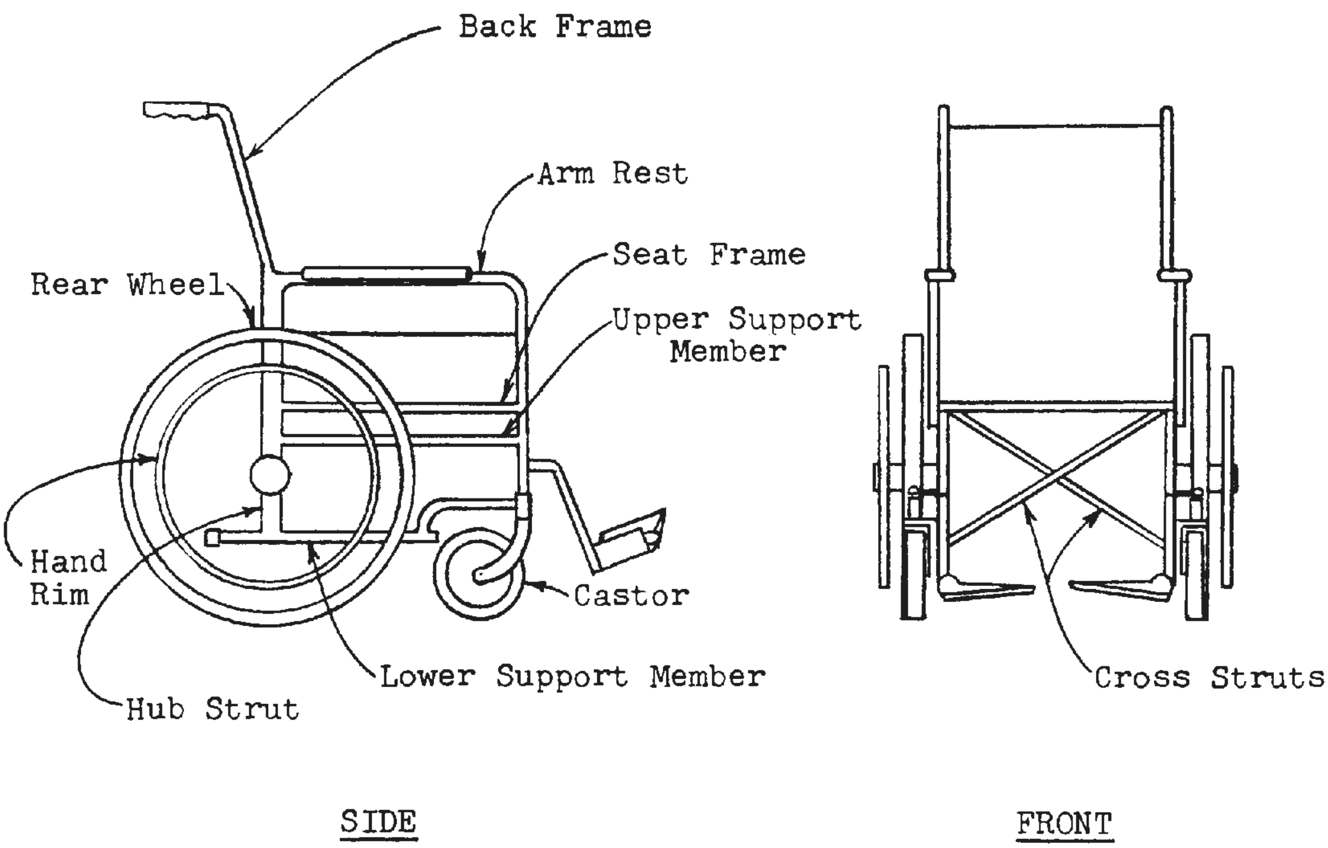
The description of right and left refers to the wheelchair occupant's right and left. In the side-facing tests, the left wheel (rear wheel) is the wheel nearer the front of the bus.

It was noted in the first report and will be repeated here: The use of a shoulder harness is necessary to reduce head and body injuries. A shoulder harness restraining the upper torso did minimize head and body impact (test 1966).

The same 50th percentile male anthropomorphic dummy (165 pounds) occupied each of the wheelchairs.

All references to wheelchairs are to the manually propelled type unless the electrically-powered type is specifically mentioned.

A figure of the wheelchair members and terms used in the description of the crash tests is shown on Figure 5. Table 1, is a summary of the results of the individual tests.



TERMS USED IN DESCRIBING WHEELCHAIRS

FIGURE 5

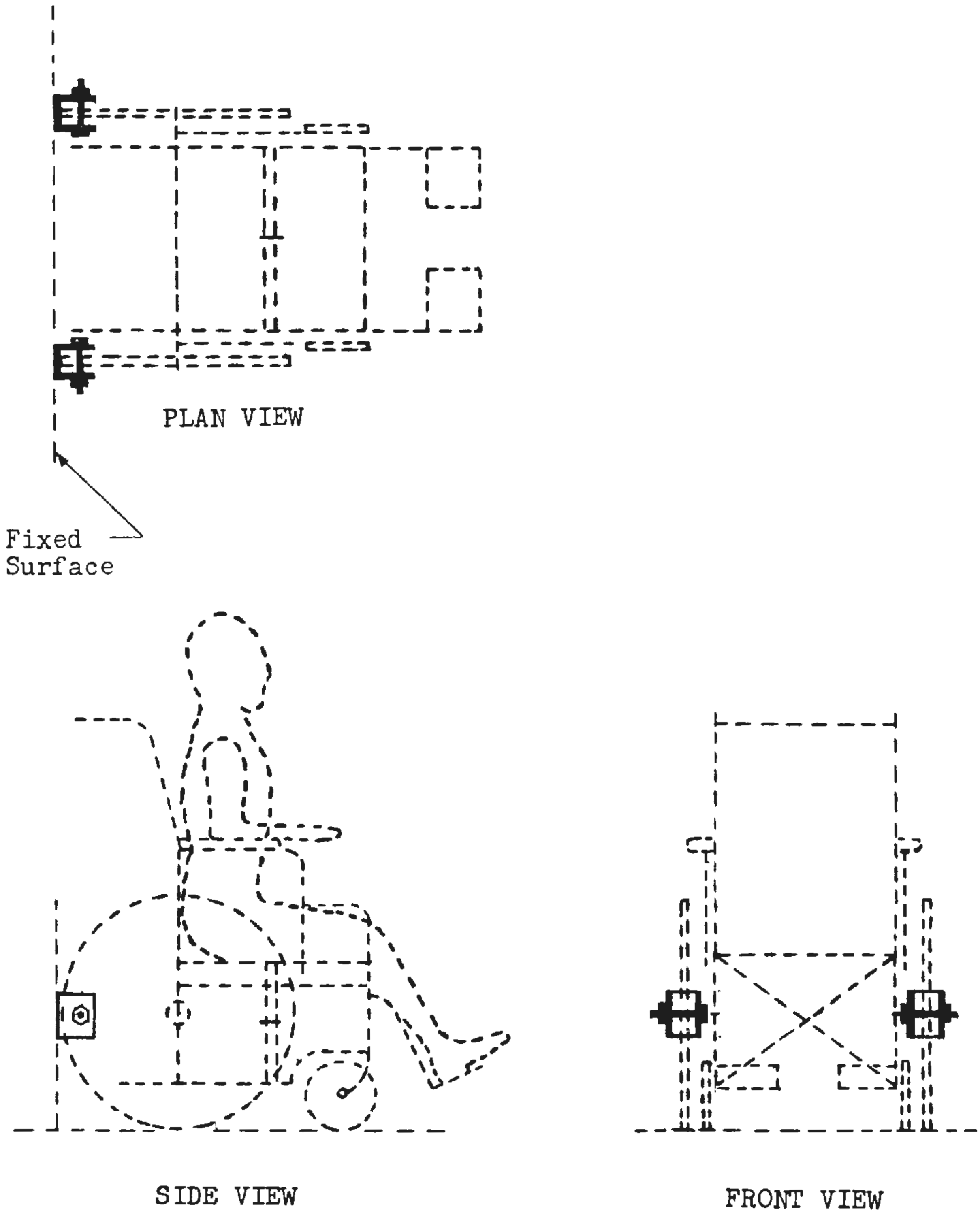
PHASE III TESTS

The following is a summary of each of the 10 tests on 8 securement systems. Because all these systems have been discussed in the first interim report, a detailed description of each of the securements will not be repeated. A drawing of each is included, however. Table 1 summarizes the variable parameters and comparison of results for Phase III tests. The number in parentheses following each test title is the test number. The box following each test title shows the velocity and deceleration of that test and those of preceding comparable tests. For clarity in reading, the velocity and g levels in the text of the section are rounded to the nearest whole number.

Wall Rim Pin/Side-Facing Chair (1865).

Test	Vel.	Dec.
1865	20 mph	5 g's
1072	19 mph	12 g's
1073	11 mph	9 g's

The test was conducted with the manual wheelchair in the side-facing mode secured by a wall rim pin system. Run at 20 mph and a reduced deceleration rate of 5 g's, this test was to compare results with Phase I test 1072 conducted at the same velocity and a deceleration rate of 12 g's and with test 1073 conducted at 11 mph and 9 g's.



WALL RIM PIN

Figure 6

In test 1865 the left wheel (nearer front of bus) twisted and bent away from the securement and the spokes of the right wheel detached from the hub. While the wheelchair tilted 40 degrees, the dummy's torso leaned 90 degrees and the dummy's head whipped severely, striking the armrest of the simulated longitudinal seat.

This test resulted in a head excursion of 49 inches, which fell between the previous two head excursion values. Test 1073 resulted in a head excursion of 44 inches, and 1072 had a head excursion of 61 inches. Test 1865 suffered major[1] wheelchair damage as did test 1072 with the comparable velocity. External props were not used in tests 1072 and 1073. Had the simulated arm rest and stanchion been installed, with the amount of excursion measured, the dummy might have come into contact with the envelope elements in both tests and the HIC values could have been greater. In test 1865 the dummy struck the simulated steel armrest resulting in the HIC of 1346. This HIC cannot be fairly compared with the other two test HIC's because they had different envelope settings.

1 Degree of wheelchair damage (major, moderate and minor) was defined in the first interim report but will be presented here for simplicity and clarity:

<u>Minor</u> - Damaged parts still function with very little applied effort. The chair's rolling and maneuvering ability is only slightly impaired.

<u>Moderate</u> - A great amount of effort is required to move and maneuver the wheelchair. An inexperienced and able-bodied person seated in the damaged wheelchair would find it very difficult to move or maneuver it.

<u>Major</u> - The wheelchair is so badly damaged that it cannot be rolled; it is unusable.

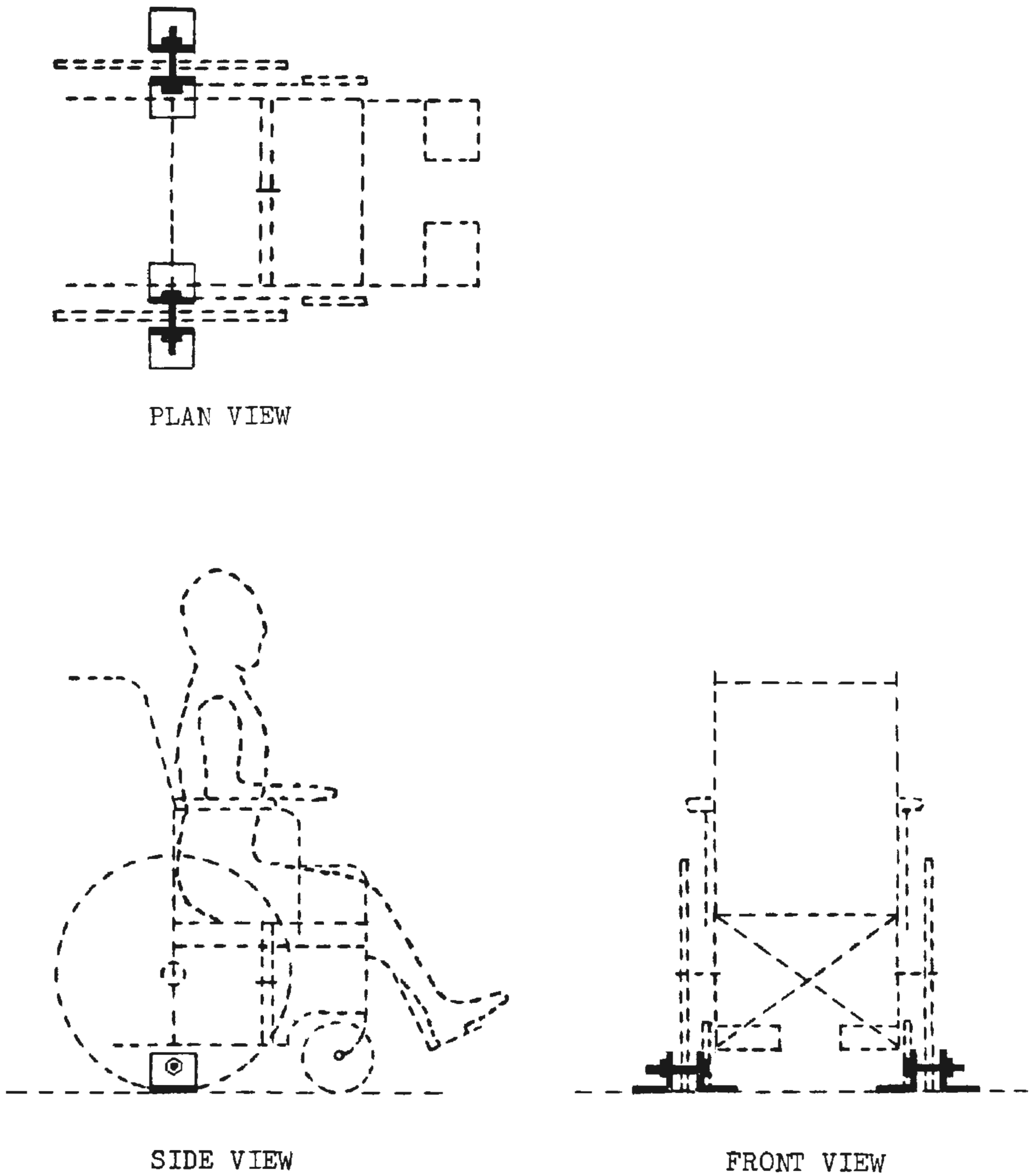
Floor Rim Pin/Side-Facing Chair (1866).

Test	Vel.	Dec.
1866	20 mph	5 g's
1070	18 mph	12 g's
1087	10 mph	10 g's

Two previous tests had been conducted for the floor rim pin system in the side-facing mode, test 1087 at 10 mph and 10 g's and test 1070 at 18 mph and 12 g's. The present test run at 20 mph and 5 g's resulted in a head excursion of 48 inches. Test 1070's head excursion was 56 inches and test 1087's was 38 inches. These excursion distances were influenced by either velocity or deceleration reductions although the velocity appeared to have the greater influence on head excursion and wheelchair damage. Test 1070 sustained major wheelchair damage as did test 1866 while test 1087, at the reduced velocity level, suffered only minor chair damage.

User and Chair Belt/Side-Facing Chair (1867).

Test	Vel.	Dec.
1867	20 mph	5 g's
1078	16 mph	10 g's
1098	10 mph	12 g's



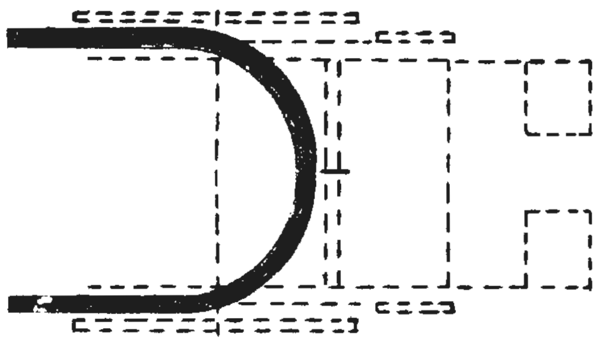
FLOOR RIM PIN

Figure 7

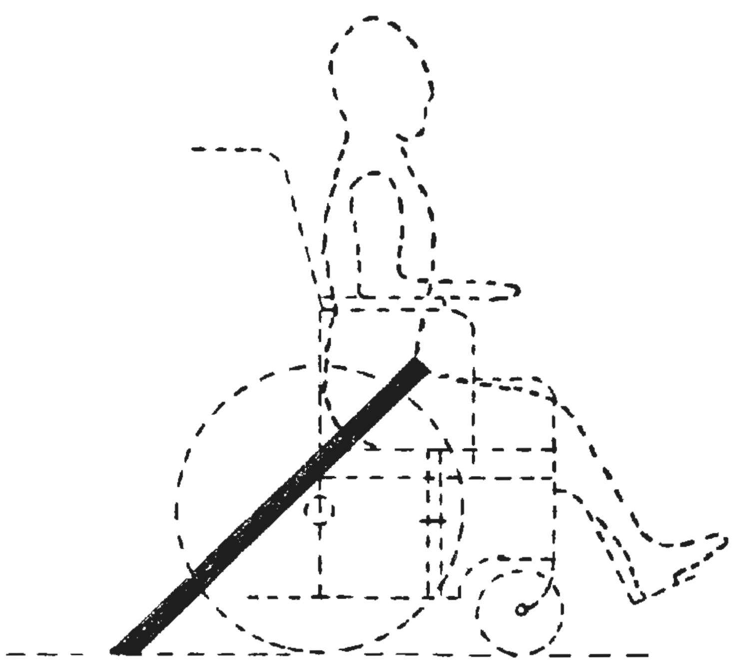
A user-and-chair-belt securement system test was performed using a side-facing dummy and wheelchair. Test 1867 was run at 20 mph and a reduced deceleration rate of 5 g's. The similar Phase I tests were at 10 mph and 16 mph and 10 g's.

The left wheel folded under severely. The wheelchair twisted 45 degrees to the left and leaned 30 degrees. The back of the dummy's head struck the simulated vertical seat cushion, rotated 90 degrees and the dummy's face struck the steel armrest. The torso leaned 60 degrees. The left hand struck the stanchion and armrest and the right hand hit the armrest.

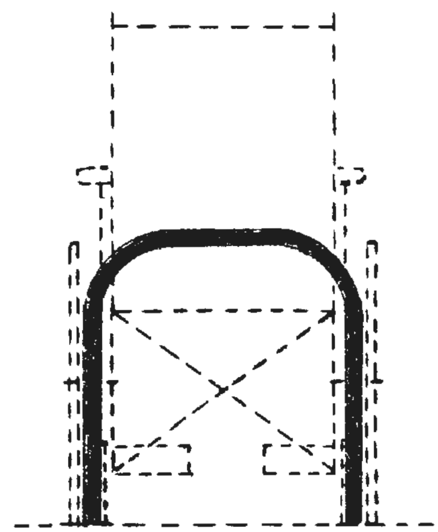
Two user-and-chair-belt securement system tests were performed in the side-facing direction in the Phase I tests. Test 1078 was run at 16 mph and 10 g's and test 1098 at 10 mph and 12 g's. Both had a head excursion of 44 inches as compared with 45 inches for test 1867. The greater velocity and reduced deceleration level of test 1867 did not vary the head excursion appreciably when compared with the head excursion values for 1078 and 1098. Both earlier tests did not have a simulated bus hardware envelope to constrain the dummy's movement as did test 1867. The comparsion of head excursion values, in this case, was not representative of the velocity and deceleration variations. The amount of chair damage, however, was correlated to speed. Test 1867, with the greater speed, encountered major wheelchair damage while tests 1078 and 1098 sustained only moderate wheelchair damage.



PLAN VIEW



SIDE VIEW



FRONT VIEW

USER AND CHAIR BELT

Figure 8

The securement belt load reached 1600 pounds, which indicates the occupant's lap area may have sustained bruises or more severe injury.

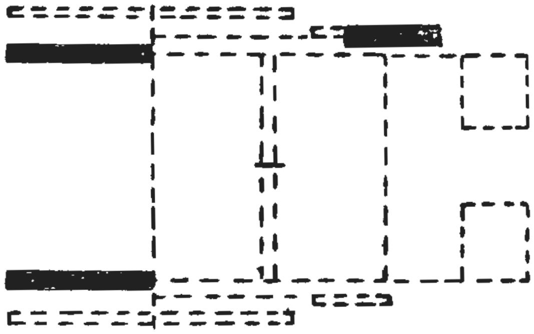
Three-Point Belt

Two tests were conducted with the three-point belt securement system; one with a side-facing manual wheelchair and the other with a forward-facing electric powered wheelchair.

Three-Point Belt/Side Facing (1868).

Test	Vel.	Dec.
1868	21 mph	5 g's
1184	20 mph	10 g's

The side-facing manual chair was tested at 21 mph and a reduced deceleration level of 5 g's. Phase I test 1184 was run at 20 mph and 10 g's. The lower deceleration level for test 1868 resulted in a lower HIC value than that of test 1184. The deceleration reduction may not be the only reason why the HIC value was low for test 1868. In test 1868, the back of the dummy's head grazed the vertical seat, the head rotated and missed the steel arm rest resulting in a minor HIC of 50. In test 1184, the severe blow on the dummy's forehead resulted in a HIC of 1532. The HIC value depended upon the chance of dummy head strike.



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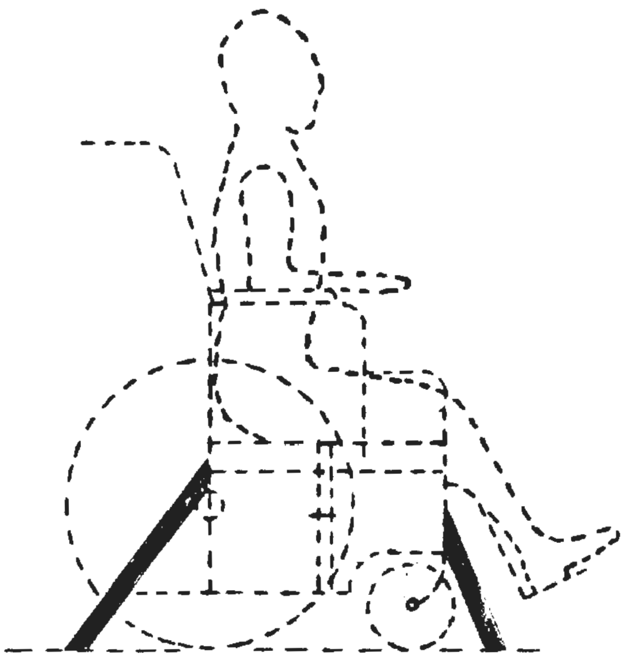
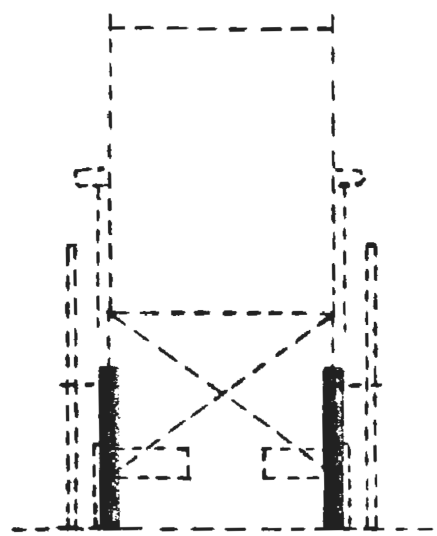


SIDE VIEW



FRONT VIEW

THREE POINT BELT

Figure 9

Test 1868's lower deceleration also decreased the head excursion, which was 45 inches versus the head excursion of 52 inches for test 1184. Reducing the deceleration level did not exert as great an influence on chair impact. The wheelchairs in both tests sustained major damage.

Three-Point Belt/Forward Facing (1880).

Test	Vel.	Dec.
1880	22 mph	10 g's
1183	20 mph	12 g's

The forward-facing electric powered wheelchair tested at 22 mph and 10 g's had a greater effect on the user belt load and HIC value than the Phase I forward facing manual wheelchair of test 1183 run at a similar speed of 20 mph and deceleration rate of 12 g's. The increased weight of the electric wheelchair resulted in a doubling of the user belt load, 920 lbs., and a fatal HIC value. Both tests sustained moderate wheelchair damage. The dummy in the manual chair (1183) suffered minor body impact and a minor head strike on the legs. The electric wheelchair dummy (1880) sustained a severe forehead strike on the steel armrest.

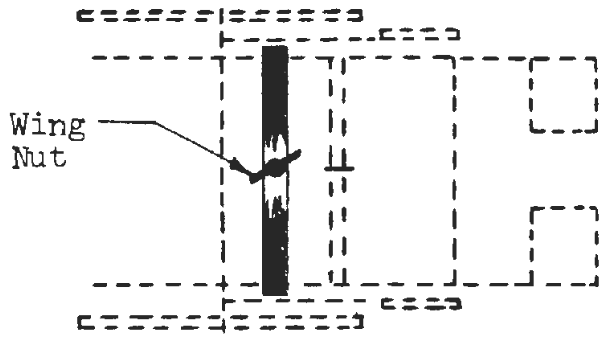
In the initial comparison of head excursion, test 1183 had a larger head excursion (50") than test 1880 (41"). This did not correlate with the extremely large HIC and severe forehead strike of test 1880 so test 1183 was scrutinized again. The reinspection of the dummy action in test 1183 revealed an error in the previous head excursion calculation. The dummy's head did not travel as far forward as the armrest. The calculated 50-inch head excursion exceeds the horizontal distance between the centerline of the dummy's head and the armrest. The head excursion in test 1183 was recalculated as 39" and the prior publication (1st interim report) should be corrected to reflect this excursion value.

Rear T-Bar System/Side-Facing Chair (1876).

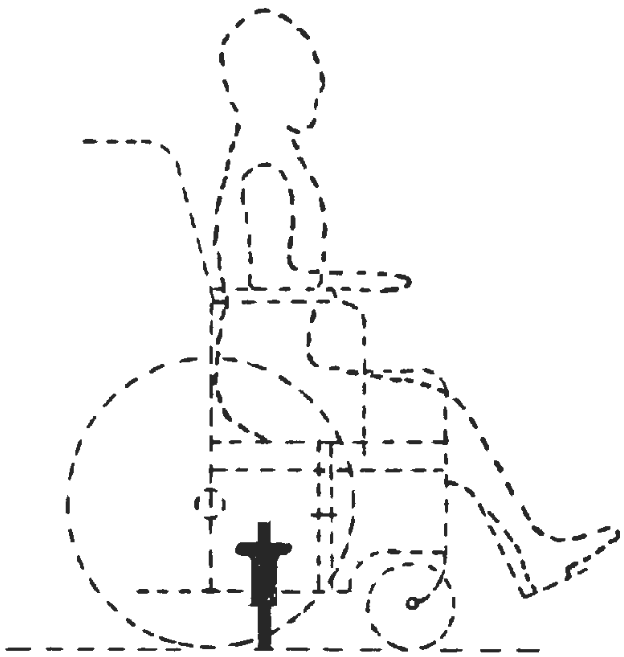
Test	Vel.	Dec.
1876	11 mph	5 g's
1122	19 mph	12 g's

A test was performed with the occupant and wheelchair in the side-facing orientation. The decreased speed of 11 mph coupled with a lower deceleration rate of 5 g's resulted in minimal damage when compared with the previous test 1122 run at 19 mph and 12 g's.

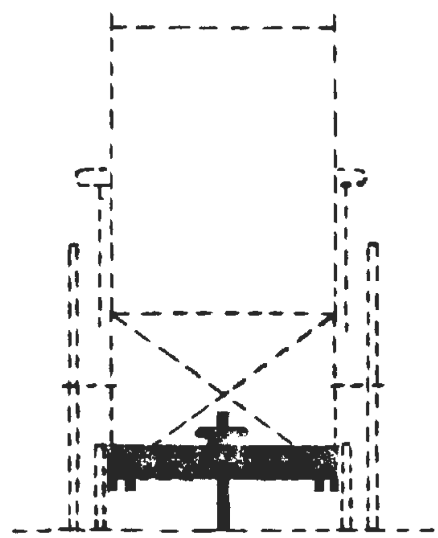
There was a 48% reduction in head excursion, 26 inches versus 54 inches. No dummy strike occurred. Minor chair damage resulted instead of the major chair damage experienced in the first test run at the greater speed and deceleration rate.



PLAN VIEW



SIDE VIEW



FRONT VIEW

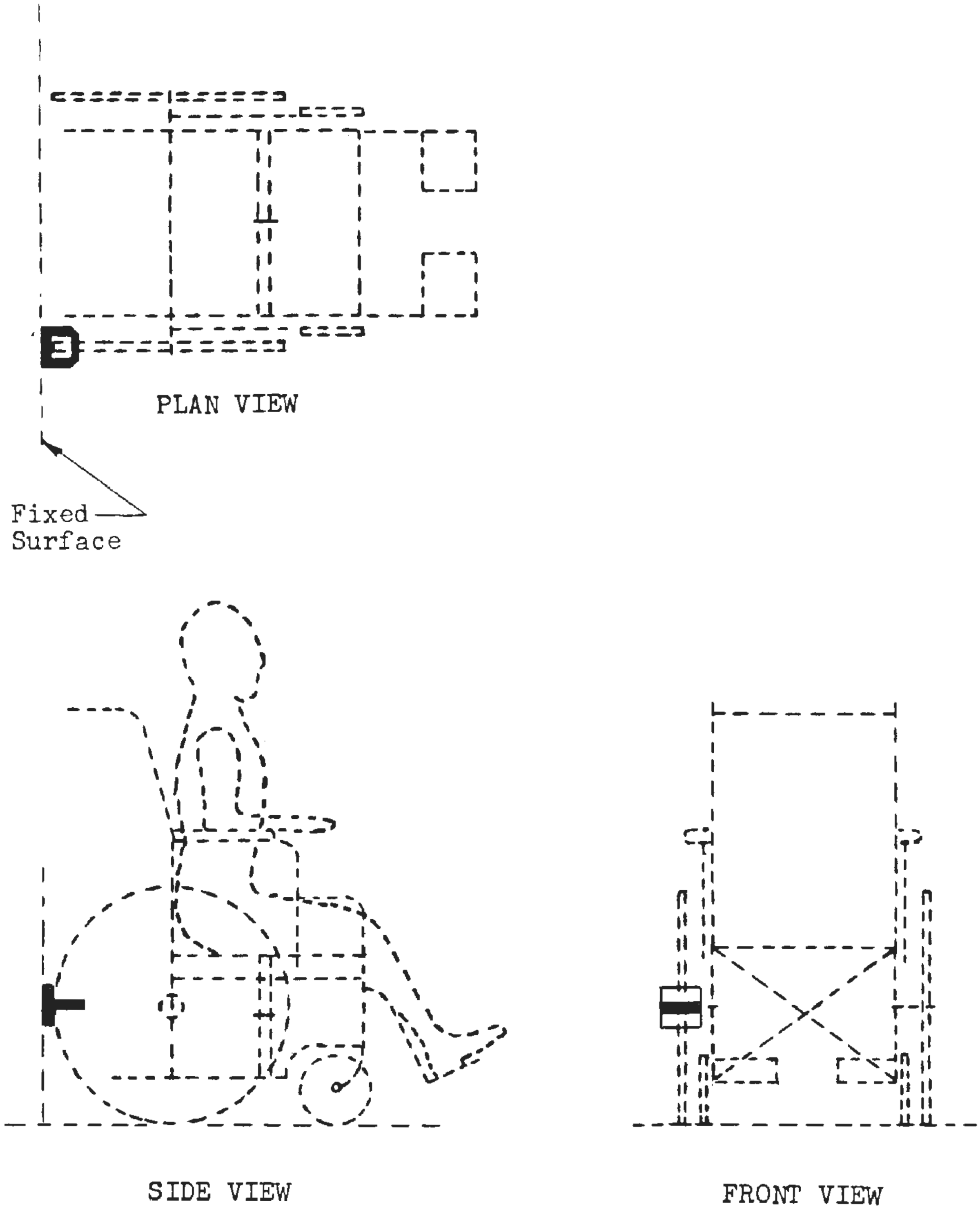
T-BAR/REAR POSITION

Figure 10

Single Rim Latch/Forward-Facing Chair (1882).

Test	Vel.	Dec.
1882	10 mph	4 g's
1187	20 mph	11 g's
1196	20 mph	10 g's
1197	20 mph	10 g's

This single rim latch is a proprietary securement modified by the manufacturer to strengthen the attachment that failed in two of the previous tests (1187 and 1196). The speed of test 1882 was reduced to 10 mph and the deceleration rate was reduced to 4 g's. A prior test on a strengthened attachment (1197) was run at 20 mph and 10 g's. The earlier (1197) testing resulted in major chair damage with a complete wheel failure. Test 1882 experienced a reduction in head excursion, 35 inches versus the 54 inches in test 1197, and no head, hand, or arm strikes. The left rear wheel in the latest test still experienced major damage but not to the same extent as in test 1197. The spoke wheel structure proved to be a weak securement link. The load stress on the securement system and wheel was compounded by attaching to one point only. Major wheelchair damage was incurred at the reduced velocity and deceleration level.



SINGLE RIM LATCH

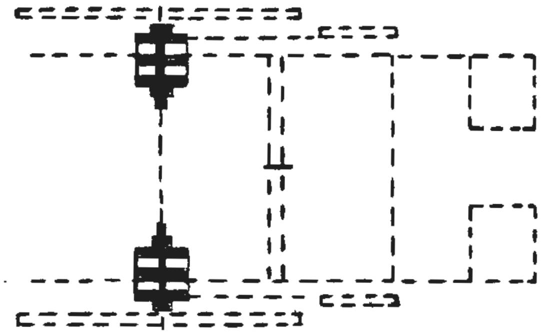
Figure 11

Frame Anchor/Forward- and Side-Facing Chairs (1884 and 1887).

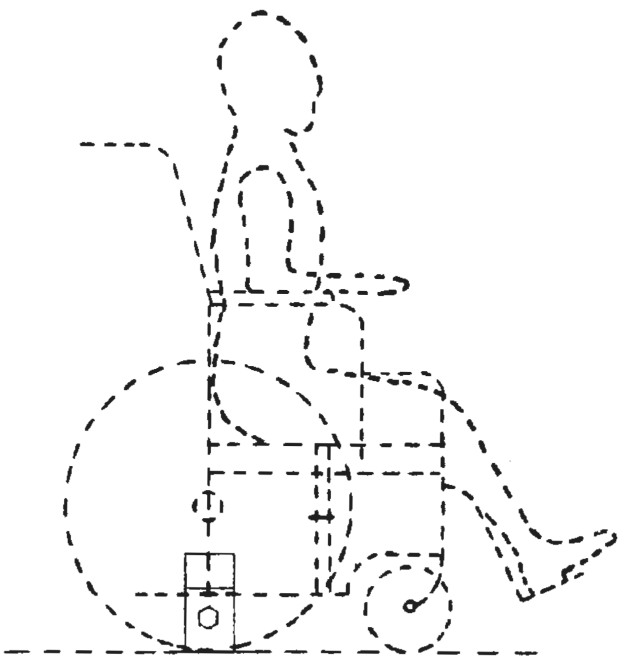
Test	Vel.	Dec.
1884	20 mph	9 g's
1887	20 mph	9 g's
1235	20 mph	10 g's

The original test (1235) on the frame anchor securement system in a forward-facing orientation was performed on a manual chair. Two new tests were conducted; one forward facing (1887) and one side facing (1884), both utilizing electric wheelchairs. They were run at a speed and decleration rate similar to test 1235's speed of 20 mph and deceleration of 10 g's.

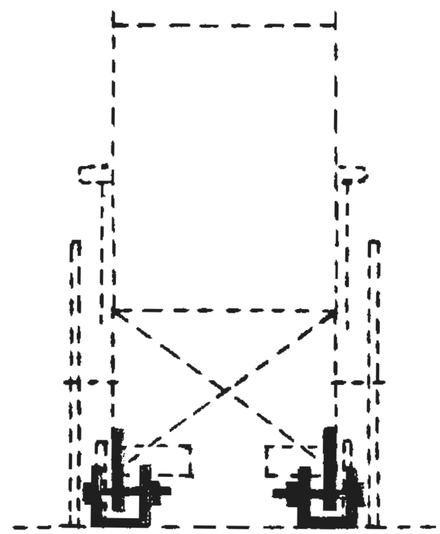
The side-facing electric wheelchair test 1884 was run at 20 mph and 9 g's. It resulted in a head excursion of 41 inches and a severe temple strike on the left forearm. There was major wheelchair damage.



PLAN VIEW



SIDE VIEW



FRONT VIEW

FRAME ANCHOR

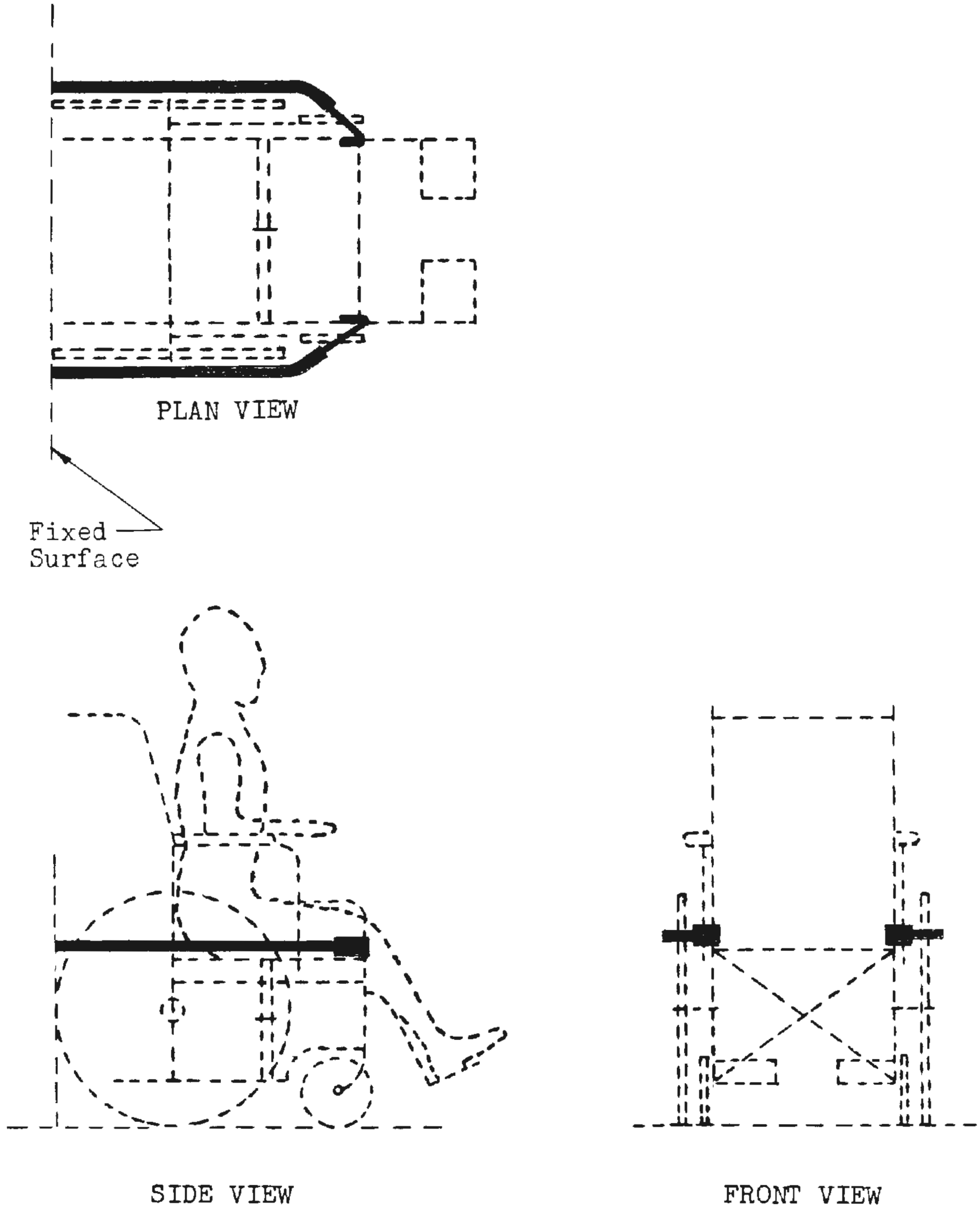
Figure 12

The forward-facing electric wheelchair test 1887 was run at 20 mph and 9 g's. Compared with the original forward-facing manual chair test 1235, test 1887 had a greater head excursion, 42 inches versus 39 inches, and the dummy's head and arms struck the simulated armrest in test 1887; whereas, the head lightly struck the dummy's leg in test 1235. The HIC values cannot be compared because the head accelerometer wire leads were damaged during the latest test and the data was not transmitted. The greater weight of the electric powered chair caused major wheelchair damage in test 1887 while only moderate wheelchair damage occurred in test 1235.

Horizontal Bars/Side-Facing Chair (1885).

Test	Vel.	Dec.
1885	11 mph	5 g's
1186	20 mph	12 g's

Test 1885, using a wheelchair in a side-facing orientation, was run at a reduced level, 11 mph/5 g's. A prior test, 1186, run at 20 mph/12 g's resulted in major wheelchair damage. The head excursion, belt loads and injury criteria in test 1186 were invalid because the back up tether came into play when the horizontal bars slid forward in the anchorage track. Test 1885 was tested at the reduced level because the securement system failed at the greater 20 mph/12 g's level and also because the



HORIZONTAL BARS

Figure 13

commercial horizontal bar securement was an easy-to-secure system requiring minimal user effort.

The securement succeeded in maintaining contact with the wheelchair in test 1885. There was a minimal HIC of 4 and a CSI of 0. The dummy leaned 75° to the left with a forward head excursion of 35 inches. There was minor chair damage with the left wheel bent about the bottom rail.

The following discussion is a summary of the six additional tests performed on three securement systems and one test using a padded barrier as the only securement. The single-rim latch securement system is used in many transit buses in California. Previous tests were supplemented with additional tests to provide a complete series. The belt-around-the-armrest restraint is similar to the user-and-chair-belt securement tested in Phase I. While the user and chair belt looped around the dummy's waist, the belt around the armrest, as its title implies, looped around the vertical posts supporting the armrests and over the dummy's knees. A new securement simulated the automatic rim pin system, currently used on some transit buses.

Single Rim Latch. Three additional tests were conducted with the anthropomorphic dummy seated in a forward-facing wheelchair secured by the single-rim-latch system. In all the single-rim-latch tests, the secured wheel attempted to tear away from the securement. Because the wheelchair was attached at this one point, all the impact force was felt by that attachment. Phase II's single rim tests 1187 and 1196 resulted in release of the securement during the crash simulation. The mechanism was modified by Minicars in test 1197 so it would not fail during the dynamic crash event. This securement system proved successful but the wheelchair suffered major damage and the dummy struck its left shoulder on the stanchion. Phase III's test 1881 represented the first manufacturer-modified, i.e., reinforced to prevent failure, single-rim-latch test. Run at a reduced speed and deceleration, the latch mechanism held and the dummy did not incur any strikes, but the wheelchair suffered major damage. The present three tests were conducted to provide new information on the modified proprietary securement system.

Single Rim Latch/Forward Facing (1967,1968).

Test	Vel.	Dec.
1967	21 mph	5 g's
1968	20 mph	5 g's

Test 1967, utilizing a manual wheelchair and run at a speed of 21 mph and a reduced deceleration of 5 g's, resulted in major wheelchair damage and a dummy head excursion of 52 inches.

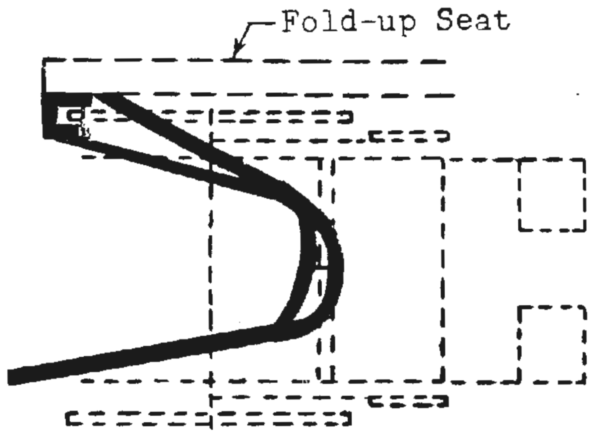
Test 1968 utilized an electric powered wheelchair and was run at 20 mph and 5 g's. The dummy's head travelled 54 inches horizontally and the wheelchair sustained major damage with complete failure of the left wheel. A comparison of the severity of the damage on the manual wheelchair versus the electric powered chair reinforced the conclusion that the additional weight of the electric powered chair proved more stressful to the dummy and wheelchair. In both tests, the dummy's right shoulder struck the stanchion.

Single-Rim-Latch With Upper Torso Belt/Forward Facing (1966).

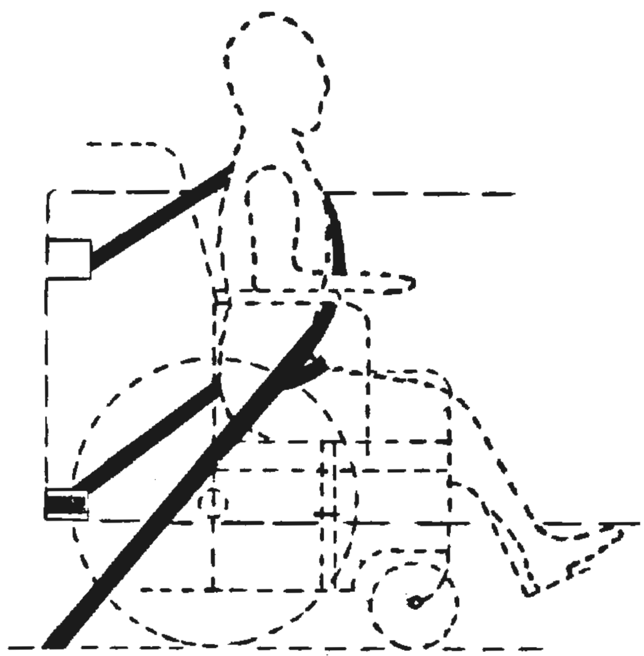
In test 1966, a single-rim-latch system secured the left rear wheel of the manual wheelchair and an automotive-like upper torso and lap belt system secured the wheelchair occupant. See Figure 14. The upper torso belt was attached to the sled structure behind the dummy's right shoulder. It passed across the left shoulder, down across the right hip and then to the floor anchorage at the rear of the wheelchair. The lap belt attached to the sled structure on the left side and to the upper torso belt at the right hip. Note that the belt system partially restrains the wheelchair through the occupant's body.

Test 1966 was run at 20 mph and 5 g's. The chair rotated to the left as in tests 1967 and 1968 which were run at the same speed and decelerated rate. Also, the left rear wheel was not destroyed as in the other two tests. It was only dented at the rim latch contact point. The three-point occupant belt not only reduced the wheelchair damage to a dent at the rim latch point, it restrained the dummy to permit only 12 inches of head excursion and almost zero rotation about the hips. The belt load was 590 pounds compared to 480 pounds in test 1967 and 150 pounds in test 1968. The HIC and CSI for test 1966 were 22 and 24 whereas they were 78 and 62 for test 1967 and 150 and 129 for test 1968.

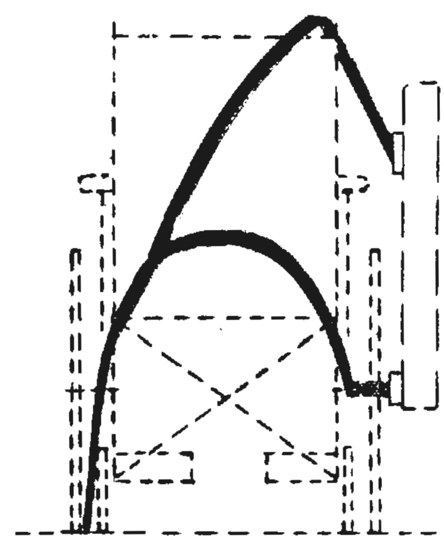
Test 1966 effectively demonstrates the value of an upper torso belt. If the backrest of the wheelchair can be adequately



PLAN VIEW



SIDE VIEW



FRONT VIEW

SINGLE RIM LATCH AND THREE-POINT BELT

FIGURE 14

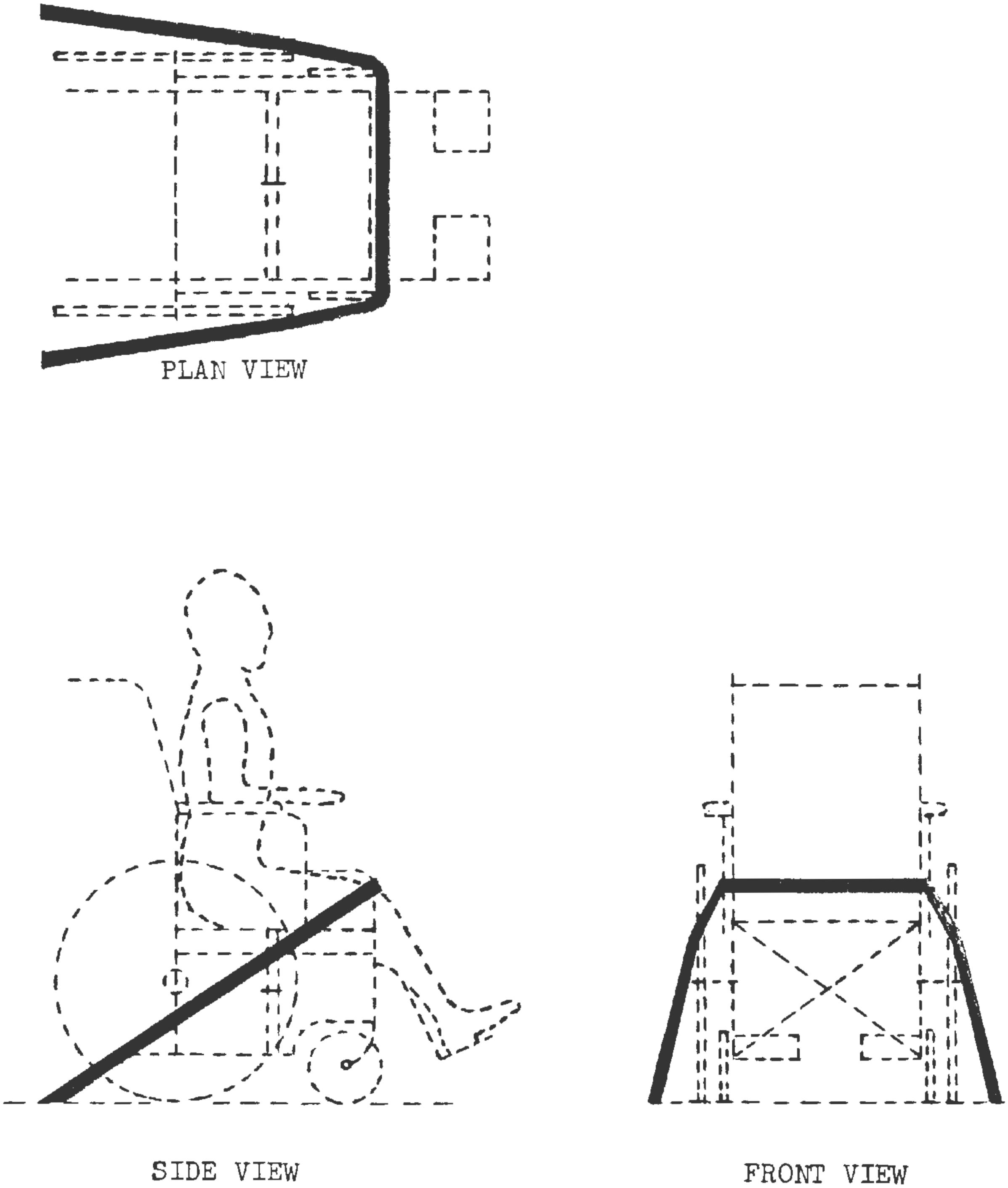
reinforced, the upper torso restraint could be attached there and the above mentioned problem of the body restraining the wheelchair would be eliminated. Some wheelchair users, however, do not have the manual dexterity or upper torso mobility to manipulate the latching mechanism.

Belt Around Armrest. The-belt-around armrest system consists of a belt anchored to the floor behind the wheelchair and attached across the front of the armrests' front vertical support tubes and over the dummy's knees (Figure 15). This securement is similar to the user-and-chair-belt securement tested in Phase I and II. The user and chair belt was also anchored to the floor behind the wheelchair but differed from the belt around armrest in that it looped around the user's waist and did not require additional securement (to secure dummy to chair). The belt around the armrest securement system did not secure the user to the chair, requiring the dummy to employ a lap belt attached to the chair axle.

Belt Around Armrest/Forward Facing (1970 & 1971).

Test	Vel.	Dec.
1970	21 mph	10 g's
1971	21 mph	10 g's

Two wheelchair tests, one manual (1970) and one electric (1971), were conducted with the dummy and chair facing forward. For both



BELT AROUND ARMREST

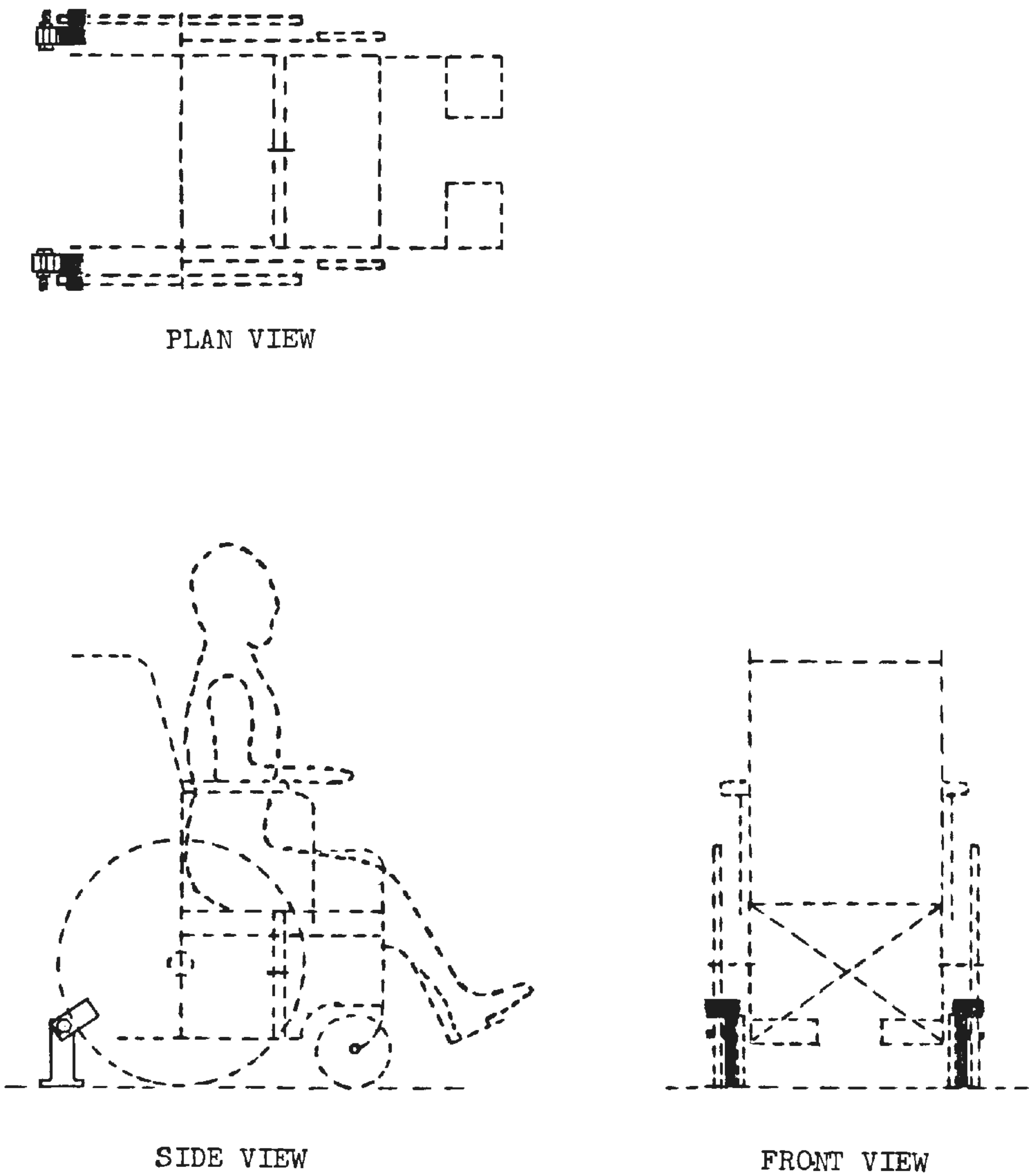
FIGURE 15

tests the sled velocity was 21 mph and the deceleration rate was 10 g's.

The manual wheelchair suffered moderate damage. The 50th percentile dummy jackknifed about the waist and the head hit its shin. The head excursion was 32 inches.

The greater weight of the electric wheelchair caused major wheelchair damage. Again, the dummy jackknifed about the waist. Due to the greater force exerted on the securement, the wheelchair belt stretched further and the head struck the simulated armrest. The head excursion was 39 inches, which is greater than the head excursion of the dummy in the manual chair; the excursion distance was limited by the head striking the simulated armrest.

Automatic Rim Pin. The commercial version of the automatic rim pin securement system consists of two horizontal fingers which are spaced about 18 inches apart. After the wheelchair has backed into the securement area, the fingers are mechanically moved horizontally, by the wheelchair user, until they move past the wheel rims. The system was simulated by a bolt and a bracket restraining the wheel rims at the same location as with the commercial unit. A schematic of the securement system is shown in Figure 16.



AUTOMATIC RIM PIN

FIGURE 16

Automatic Rim Pin/Forward facing (1976).

Test	Vel.	Dec.
1976	21 mph	11 g's

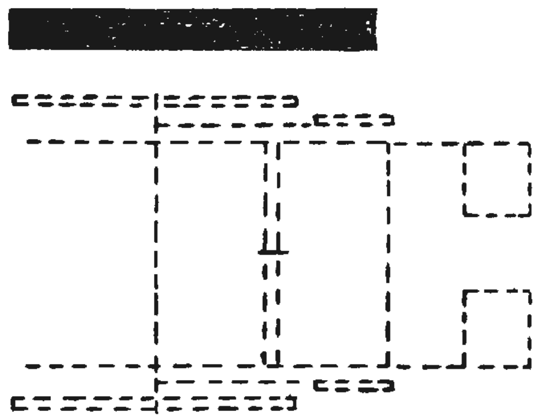
A manual wheelchair was tested in the forward-facing mode at 21 mph and 11 g's. The securement held. The dummy's head transversed 27 inches and struck its shin severely. The wheelchair was moderately damaged.

Padded Side Panel. A panel of plywood was covered with a three-inch thickness of Ensolite, a styrofoam-like energy absorbing material similar to that used in the dash of an automobile. The panel was placed perpendicular to the simulated bus wall and in front of the anticipated dummy and wheelchair trajectory. The wheelchair armrest was placed 4 inches from the panel, as shown in Figure 17.

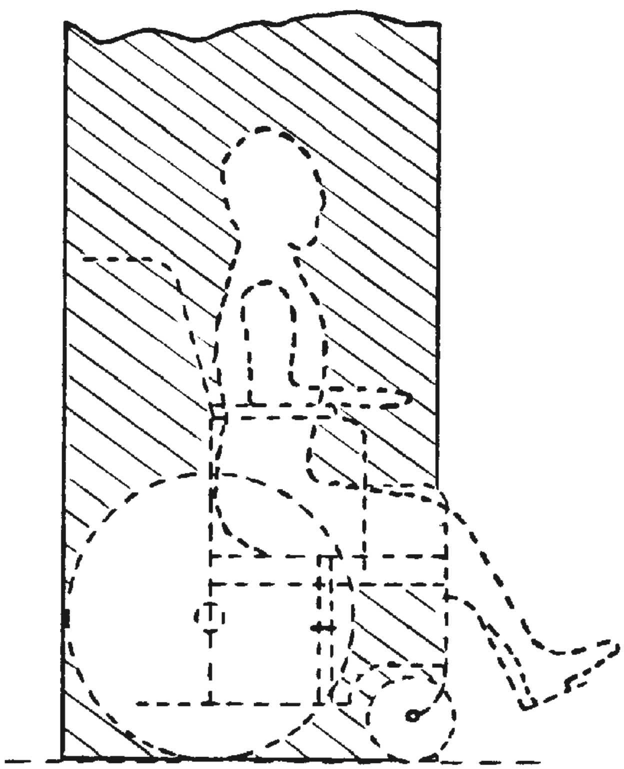
Padded Side Panel/Side Facing (1979).

Test	Vel.	Dec.
1979	21 mph	10 g's

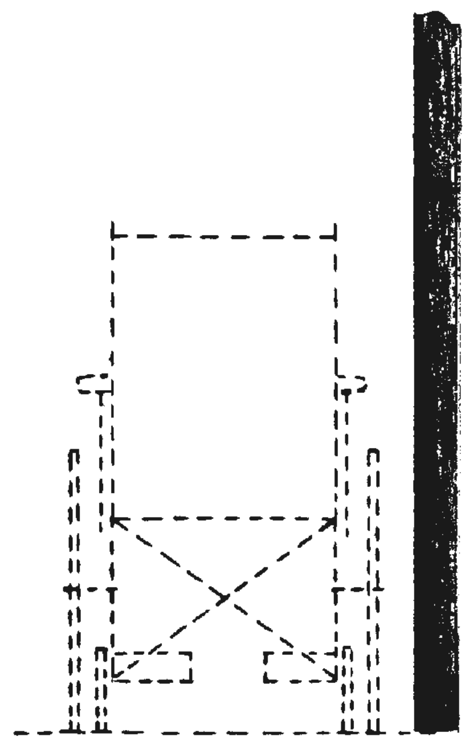
The last test of the project, run at 21 mph and 10 g's, used an unsecured wheelchair placed in the side-facing direction. The



PLAN VIEW



FRONT VIEW



SIDE VIEW

PADDED SIDE PANEL

FIGURE 17

wheelchair and occupant were thrown against the panel; then the wheelchair and dummy rebounded off the sled. In the initial strike, the dummy's head and shoulder struck the panel. The wheelchair sustained only minor damages. This was an unsatisfactory method of restraining the wheelchair and user's movement; however, one of the purposes of the test was to determine the result of not securing the chair. If the chair were secured it may prove to be one of the better restraint systems since rotation of the upper body about the hips is greatly reduced.

The panel is required to be quite large to adequately protect all combinations of wheelchairs and users; therefore, it blocks the forward view of the wheelchair user and some of the other passenger. The handicapped and ambulatory passengers have expressed opposition to such view obstructing systems. Replacing the solid panel with a nylon net could be one solution to this objection. Further testing of the padded side panel is not planned.

SYSTEM EVALUATION

Summary

Table I summarizes the performance of each securement concept tested with respect to selected evaluation parameters. The evaluation of the effectiveness of the securement system in absorbing initial impact and in maintaining positive contact with the wheelchair after the initial impact, and the degree of difficulty to self-secure are presented in Table II. A new column, "test reason" showing the purpose of the test, is included.

As in the interim report, the effectiveness of the securements was rated as either good or poor, according to the following definitions:

Good: The securement retained positive contact with its attachment point(s) on the wheelchair throughout impact and prevented the wheelchair from tipping over or from making an otherwise undesirable movement. If the system is judged satisfactory under the conditions tested, it is acceptable.

Poor: The securement either lost contact with the chair, did not prevent it from tipping over during impact, or allowed it to make undersirable movements. If the system is judged not satisfactory under the conditions tested, it is unacceptable.

SYSTEMS, FACING DIRECTION / TEST PARAMETERS	WALL RIM PIN	FLOOR RIM PIN	USER CHAIR BELT	3 POINT BELT		REAR T-BAR	SINGLE RIM LATCH	FRAME ANCHOR		HORIZONTAL BARS
	SIDE	SIDE	SIDE	SIDE	FORWARD	SIDE	FORWARD	SIDE	FORWARD	SIDE
TEST NO.	1865	1866	1867	1868	1880	1876	1882	1884	1887	1885
SLED SPEED (mph)	20.3	20.3	20.3	21.3	21.9	10.9	10.1	19.6	20.3	10.6
SLED DECELERATION (g's)	5.0	4.8	5.3	5.2	9.5	5.0	4.3	9.4	9.3	4.8
CHAIR TYPE	Manual	Manual	Manual	Manual	Electric	Manual	Manual	Electric	Electric	Manual
FOOTREST TYPE	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid
SEAT BELT	To Axle	To Axle	To Floor	To Axle	To Axle	To Axle	To Axle	To Axle	To Axle	To Axle
SEAT BELT LOAD (lbs)	NA	580	1600	300	920	120	300	900	350	100
HEAD EXCURSION (inches) 1	56	55	51	51	50	28	36	52	47	39
DUMMY STRIKE	Severe head strike on armrest of seat	Side of head struck back of vertical seat cushion	Back of head struck seat upright cushion; face on steel armrest	Slight head strike on foam seat back cushion; slight left hand strike on steel armrest	Severe head strike on forehead from steel armrest; Rt. hand on seat armrest; Lt. hand on vert. cushion	NONE	NONE	Left temple struck left forearm severely; left forearm struck steel armrest	Severe forehead strike on steel seat armrest Rt.& lt. forearm struck armrest	NONE
HIC 2	1346	78	174	50	2078	10	4	472	NA	4
CSI 3	62	28	44	34	156	Ø	Ø	34	58	Ø
WHEELCHAIR DAMAGE	Major	Major	Major	Major	Moderate	Minor	Major	Major	Major	Minor
COMMENTS	Wheelchair leaned 40° to lt & dummy's torso leaned 90°.	Wheelchair leaned 30° & twisted 20° left. Dummy's torso leaned 80°.	Wheelchair leaned 30° & twisted 45°. Dummy's head rotated 90° & torso leaned 60°.	Wheelchair leaned 30° & rotated 10° to left. Dummy's torso leaned 60°.	Dummy's torso leaned forward 80°.	Wheelchair leaned 10°. Dummy's torso leaned 45°.	Wheelchair rotated 20° left. Dummy's torso leaned forward 45°.	Wheelchair leaned 30°. Dummy's torso leaned 90°.	Accelerometer wires damaged	Wheelchair leaned 20°. Dummy's torso leaned 75°.

1 = Forward, relative to pretest position;
2 = Head Injury Criterea;
3 = Chest Severity Index;
NA = Not Available
NE = No Envelope provided;
NR = Not Relevant (The securement failed; therefore, results are not applicable.)

SUMMARY OF DYNAMIC TEST RESULTS - PHASE III

TABLE I

SYSTEM TESTED/ FACING DIRECTION / TEST PARAMETERS	SINGLE RIM LATCH							BELT AROUND ARMREST		AUTO RIM PIN	PADDED SIDE PANEL
	OLD		MODIFIED OLD	PHASE 3	PHASE 4			PHASE 4		PHASE 4	PHASE 4
	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	FORWARD	SIDE
TEST NO.	1187	1196	1197	1882	1967	1966	1968	1970	1971	1976	1979
SPEED	19.8	19.9	19.7	10.1	20.8	20.2	19.8	20.8	20.5	21.2	20.7
DECELERATION	11.0	10.0	10.0	4.3	5.0	4.9	4.8	9.5	10.0	11.0	9.6
WHEELCHAIR TYPE	Manual	Electric	Manual	Manual	Manual	Manual	Electric	Manual	Electric	Manual	Manual
FOOTREST	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid
USER BELT	Lap To Axle	Lap and Shoulder To Bus	Lap To Axle	Lap To Axle	Lap To Axle	Lap and Shoulder To Bus	Lap To Axle	Lap To Axle	Lap To Axle	Lap To Axle	Lap To Axle
BELT LOAD	NM	1400	180	300	480	590	150	Lap: 260 W/C: 1500	Lap: 140 W/C: 1820	770	280
HEAD EXCURSION	NM	34	54	36	57	15	61	48	47	50	NM
DUMMY STRIKE	NM	Head On Right Leg	Shoulder On Stanchion	None	Right Shoulder Hit Stanchion	None	Right Shoulder Hit Stanchion	Head Struck Shins	Head Struck Armrest	Head Struck Shins	Head and Shoulders Struck Padding
HIC	NM	622	128	4	78	22	150	670	Fatal 1437	Fatal 1029	351
CSI	NM	124	98	Ø	62	24	129	149	141	140	175
WHEELCHAIR DAMAGE	Major	Moderate	Major	Major	Major	Minor	Major	Moderate	Major	Moderate	Minor
COMMENTS	Securement Released Wheelchair							Jackknife At Waist	Jackknife	Jackknife At Waist	After Contact With Wall Body and Wheelchair Rotated and Fell off Sled

NM = Not Measurable

SUMMARY OF DYNAMIC TEST RESULTS
PHASE IV
TABLE 1

SYSTEM EVALUATION

TEST	SYSTEM	FACING DIRECTION	V* MPH	D* g's	WHEEL-CHAIR TYPE	HEAD EXCUR.	DEGREE OF DIFFICULTY TO SELF SECURE	CHAIR DAMAGE	INITIAL IMPACT EFFECTIVENESS	SECONDARY IMPACT EFFECTIVENESS	TEST REASON
PHASE III											
1865	Wall Rim Pin	Side	20	5	M	49"	Medium	MAJOR	GOOD	GOOD	
1866	Floor Rim Pin	Side	20	5	M	48"	High	MAJOR	GOOD	GOOD	Reduced Level ***
1867	User Chair Belt	Side	20	5	M	45"	Medium	MAJOR	GOOD	GOOD	
1868	Three-Point Belt	Side	20	5	M	45"	High	MAJOR	GOOD	GOOD	
1880	Three-Point Belt	Forward	20	10	E	41"	High	MODERATE	GOOD	GOOD	Fill Gap Electric
1876	Rear T-Bar	Side	10	5	M	26"	High	MINOR	GOOD	GOOD	
1885	Modified Horiz. Bar	Side	10	5	M	35"	Low	MINOR	GOOD	GOOD	Reduced Level ***
1882	Single Rim Latch	Forward	10	5	M	35"	Low	MAJOR	GOOD	GOOD	
1884	Frame Anchor	Side	20	10	E	41"	High	MAJOR	GOOD	GOOD	New Position
1887	Frame Anchor	Forward	20	10	E	42"	High	MAJOR	GOOD	GOOD	Heavier Chair

* V = Velocity
D = Deceleration

** M = Manual
E = Electric

*** To determine impact results at reduced levels for systems with poor performance at 20 mph/10 g's

PHASE III - SYSTEM EVALVATION
TABLE II

SYSTEM EVALUATION

TEST	SYSTEM	FACING DIRECTION	V* MPH	D* g's	WHEEL-CHAIR TYPE	HEAD EXCUR.	DEGREE OF DIFFICULTY TO SELF SECURE	CHAIR DAMAGE	INITIAL IMPACT EFFECTIVENESS	SECONDARY IMPACT EFFECTIVENESS	TEST REASON
PHASE IV											
1967	Single Rim Latch	Forward	20	5	M	52"	Low	MAJOR	GOOD	GOOD	Increased Speed 20 mph
1968	Single Rim Latch	Forward	20	5	E	54"	Low	MODERATE	GOOD	GOOD	Decreased Deceleration Rate 5 g's
1966	Single Rim Latch Upper Torso Belt	Forward	20	5	M	12"	Medium	MINOR	GOOD	GOOD	Upper Torso Belt
1970	Belt Around Armrest	Forward	20	10	M	32"	Medium	MODERATE	GOOD	GOOD	System Not Previously Tested
1971	Belt Around Armrest	Forward	20	10	E	39"	Medium	MAJOR	GOOD	GOOD	
1976	Automatic Rim Pin	Forward	20	10	M	27"	Low	MODERATE	GOOD	GOOD	
1979	Padded Side Panel	Side	20	10	M	NM	Low	MINOR	POOR	POOR	

* V = Velocity
D = Deceleration

** M = Manual
E = Electric

*** To determine effect of less severe deceleration

NM = Not Measured

PHASE IV - SYSTEM EVALUATION
TABLE II

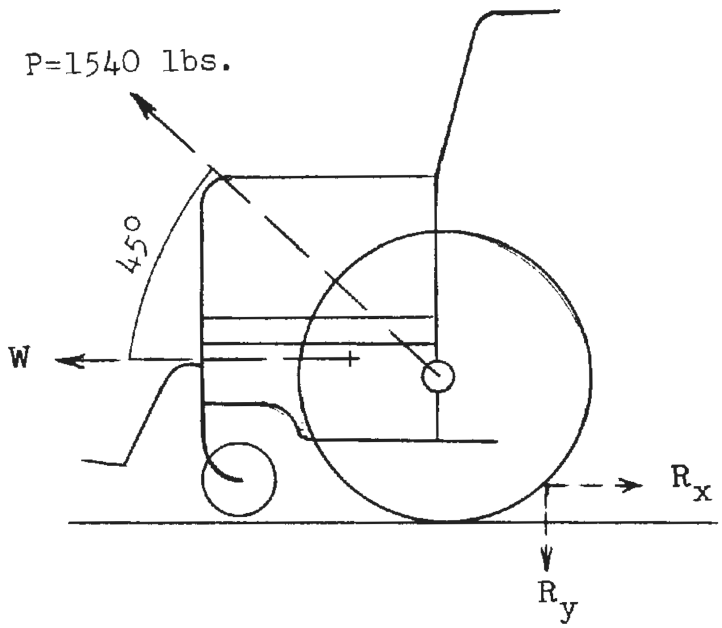
Securement Design Loads

In the First Interim Report the design load for each acceptable securement system was calculated (Page 110). Of the 17 tests in Phases III and IV, only the automatic rim pin and padded side panel systems were not previously tested and, thus, the design loads not calculated. Since the padded side panel had no wheelchair tie down and the result was unacceptable, no calculation will be made. None of the previously calculated systems were tested at a higher velocity or deceleration rate.

As in the previous calculation, the automatic rim pin used the combined dummy load (P) and chair load (W) to calculate the securement design loads (Rx and Ry). Orientation of the loads is shown in Figure 18. the calculated design loads of the automatic rim pin for a 20 mph and 10 g's crash leve, a 50th percentile male occupant, and the manual wheelchair are shown below.

	Design Loads	
System (Forward Facing)	Ry (lbs)	Rx (lbs)
Automatic Rim Pin	1600	1600

CONCLUSIONS



Automatic Rim Pin

Figure 18

CONCLUSIONS

Assuming the wheelchair user is firmly held in place by a lap belt in the type of wheelchair that was tested, the following conclusions were developed from an evaluation of the tests performed in Phases I through IV:

1. A wheelchair user can be protected from serious injury in a crash event through the use of a properly designed securement system. The system that has performed the best in the forward-facing tests conducted to date is the single-rim-latch securement coupled with an automotive-type lap and shoulder harness that is anchored to the vehicle. In this test (1966), the shoulder belt prevented the dummy from violently rotating about its lap belt as it did in most of the other forward-facing tests; therefore, it did not strike its head or arms on the simulated seat or its knees. Although this test was performed at 20 mph/5 g's, the data and films indicate it will be equally protected at 20 mph/10 g's. Additional tests at the higher g level are planned. The data and films also show that the lap and shoulder belts provided most of the restraint. The wheel rim was only slightly dented by the single rim latch, in contrast to the significant distortion experienced in most other tests using this securement. The floor rim pin, wall rim pin, frame anchor, or

automatic rim pin may be equally as good when coupled with the lap and shoulder belts.

2. Thus far, the side-facing tests have indicated this orientation is undesirable. The wheelchair user's neck, hips, and knees are subjected to bending in an abnormal direction, and the main wheels of the wheelchair usually collapse. The final test of this series (1979), placed a side-facing wheelchair and dummy next to a padded wall. The wheelchair was not secured to the vehicle. The films show that the wheelchair and dummy pressed against the padding during the deceleration phase, but both rebounded to the rear and fell off the sled at the end of deceleration. The results of this test indicate that the padded wall may be an acceptable side-facing securement if the wheelchair is restrained by a securement system that will restrict its freedom of movement during the rebound phase.

   Although the padded wall is a visual obstruction on a transit vehicle, this securment method should be further developed for the paratransit users since forward visibility is not as important there. Most paratransit vehicles can carry six side-facing wheelchairs, but only four in the forward-facing orientation; a large economic difference to the paratransit operator since these vehicles frequently have a full load of passengers.

Padded side panels need not be rectangular in shape. The visual obstruction problem could be less objectionable if the upper area is modified to remove that portion that is outside the impact area. A nylon net instead of the padding should also be considered.

3. Any type of securement that is attached to only one of the main wheels is less desirable than those attached to both wheels because the wheel is almost separated from the wheelchair at crash pulses as low as 10 mph and 5 g's. The excessive elongation of the wheel and damage to the spokes allows the chair and its occupant to move toward the front of the bus, almost assuring he/she will strike a solid object.

4. A wheelchair and its occupant can survive a 20 mph/10 g crash in a bus if they are properly secured. The securement system should symmetrically grip the wheelchair in at least two places and be designed to remain secure at the imposed loads. In addition, the occupant should be restrained with an upper torso belt and a lap belt.

5. The presently available wheelchairs are not designed to withstand crash type stresses and -- using the securement systems currently offered -- should be expected to be permanently deformed and possibly inoperable after a

crash experience. When a universally acceptable securement system becomes available, the wheelchair manufacturers should be encouraged to make a unit that will be operable after a 20 mph/10 g crash.

6. The liquid in the batteries did not spill in any of the 10 tests performed with electric powered wheelchairs.

7. In the velocity and deceleration range used in these tests, changes in velocity had a greater effect on occupant injury and wheelchair damage than did changes in deceleration rate. The lesser deceleration rate (velocity remaining constant) caused a reduction in head excursion and CSI but not as great as that caused by a decrease in impact velocity. A high incidence of dummy strikes and major chair damage still occurred at the lower g level.

8. Fixed footrests provide resistance to forward tipover in forward-facing tests.

9. Lap belts prevent the dummy from being separated from the wheelchair and should be mandatory for wheelchair users riding a bus. The lap belt should be attached in the wheel hub area to provide the proper belt-to-torso angle and to take advantage of the stronger structural members in that area.

10. Use of the electric powered wheelchairs, when compared with the manual wheelchairs, resulted in an increase in head excursion. Head or body strikes occurred in all but one of the electric wheelchair tests. Wheelchair damage was moderate to major with the majority of the electric powered chairs suffering major damage. An increase in mass, in this case using the heavier electric wheelchair, caused more intense dummy movement and increased the degree of chair damage.

11. The envelope in Phases II, III and IV testing had a negative and a positive influence on test results. Where the head excursion exceeded the envelope distance, the likelihood of a head, hand or torso strike was much greater. In a positive manner, the side wall of the bus provided additional support to the side-facing chair.

12. The HIC data did not necessarily correlate with the head excursion data. The HIC is dependent upon dummy head contact. When the head did not travel as far forward as the simulated armrest, the dummy pivoted about the waist and, depending upon how great the impact pulse, the head hit or missed the legs; the HIC reflected the situation. In tests where the dummy's head struck the armrest, the HIC was usually high. In some tests, the dummy's head cleared the armrest and the HIC was low; but the dummy hit its shoulder on the stanchion.

13. The manual wheelchair did not tip over in the belt-around-the-armrest securement test. The heavier electric powered wheelchair, likewise, remained upright in the dynamic test.

14. The automatic-rim-pin securement test run at the regular crash pulse (20 mph/10 g's) resulted in an unsatisfacory dummy strike that could be fatal to the human user.

15. The rear t-bar and horizontal bar securements, systems that rely on tension for attachment, did not perform satisfactorily during the regular 20 mph/10 g's crash event in the forward-or side-facing orientation. At the reduced levels of 10 mph/5 g's, both systems proved adequate in restraining the wheelchair throughout the dynamic event in the side-facing orientation. The dummy's action was less violent and the wheelchair's damage was less severe in the 5 g tests.

16. The seventeen tests of Phases III and IV confirm the previous conclusion that occupant excursion varied widely with the system. Therefore, the available clear envelope and removal or padding of obstructions should be major concerns in the selection and placement of the securement in a transit vehicle.

17. A minimum clear space of 30 inches wide by 53 inches long for a forward-facing wheelchair station, recommended in the first interim report, appears satisfactory when there is an adequate securement system and the user is strapped to his wheelchair with a lap belt attached to the axles.

18. All securement systems, currently in use, suffer some deficiency. Some are awkward to manipulate, others do not provide sufficient protection to the wheelchair or to the user.

19. Most handicapped persons would be expected to survive a crash without injury when secured as described above; however, the type of infirmity a handicapped person has could be aggravated by the deceleration forces causing the legs and arms of the wheelchair user to rapidly flail around. If the occupant has a condition that could be affected by such rapid and forceful movement it should be taken care of on an individual basis through the use of additional restraints.

RECOMMENDATIONS

Caltrans and UMTA should promote the development of a securement system that will provide the maximum attainable protection for the wheelchair user. Although the forward-facing orientation is recommended for public transit buses, a side-facing securement should be developed for economic reasons for paratransit buses (4 forward-facing verses 6 side-facing).

The developed system should:

- provide the maximum attainable protection for the wheelchair user in a 20 mph and 10 g crash pulse with a 50th percentile dummy in place.
- be designed for forward-facing wheelchair orientationin public transit buses and side-facing in paratransit buses -- may require two different systems.
- be adaptable to as many styles of wheelchair as possible.
- be operable by wheelchair persons with minimal arm and hand dexterity.
- attach to the wheelchair at a minimum of two symmetrical locations.

- o allow only minimal deformation and forward movement of the chair.

- o not have exposed hazardous features.

Further testing should include:

- o test the padded panel with a secured side-facing wheelchair.

- o test a nylon net in place of the padded panel, with a secured side-facing wheelchair.

- o perform tests with the lap and shoulder belts attached to the wheelchair. Many users do not have the manual dexterity to latch the belts and could have someone perform this task prior to entering the bus if the belts are attached to his/her wheelchair. Also, some of the wheelchair deceleration force is transferred to the users body when the belts are attached to the bus. When the belts are attached to the wheelchair they are subjected to the body loads only.

APPENDIX A

Appendix A

Dynamic Test Results

Following are descriptions, results, and photographs of the final 17 dynamic tests conducted. For the purpose of minimizing space, only a few representative samples of printout test data on accelerations and loads are given. All data collected will be available in a separate publication entitled "Complete Appendix to Wheelchair Securement Tests". Parts of the wheelchair are identified on Figure 5.

The following tests are grouped by type of securement.

The left side of the wheelchair is nearest the front of the bus in side-facing tests.

The text refers to the wheelchair damage in three terms:

> Minor - Damaged parts still function with very little applied effort. The chair's rolling and maneuvering ability is only slightly impaired.
>
> Moderate - A great amount of effort is required to move and maneuver the wheelchair. An inexperienced and able-bodies person seated in the damaged wheelchair would find it very difficult to move or maneuver it.
>
> Major - The wheelchair is so badly damaged that it cannot be rolled, is unusable.

TEST NUMBER: 1865

FACING DIRECTION: Side

SLED SPEED: 20.3 mph

CRASH PULSE: 5.0 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Wall rim pin

DUMMY: Lap belt to axles

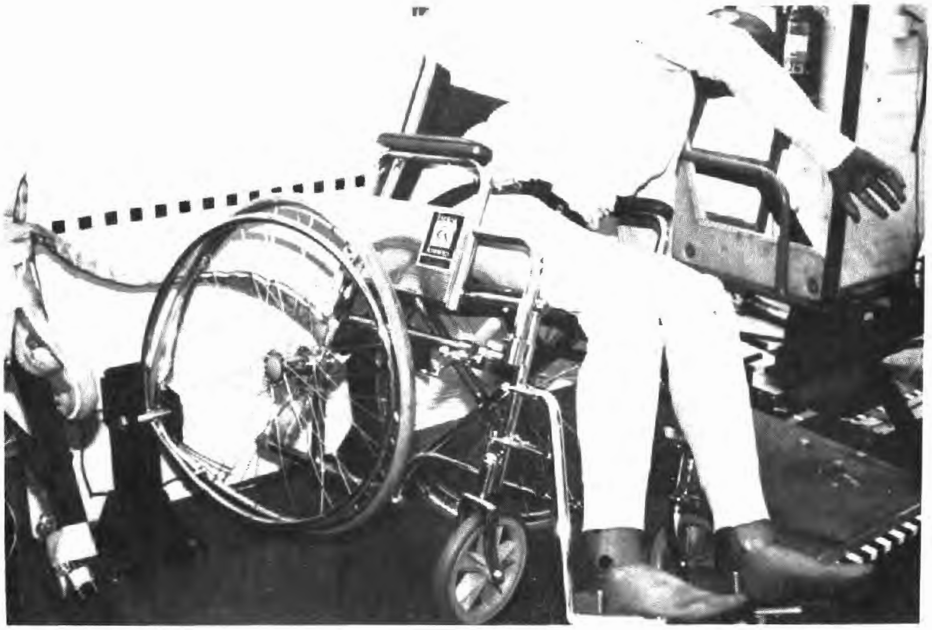
TEST ACTION:

Upon sled impact, the upper torso of the dummy leaned about 90 degrees to the left. Its left forearm struck the stanchion and the side of its head slammed into the simulated armrest. The left wheel folded under and the right wheel deformed severely as the wheelchair attempted to rotate about the left wheel (Figure A-1).

TEST RESULTS:

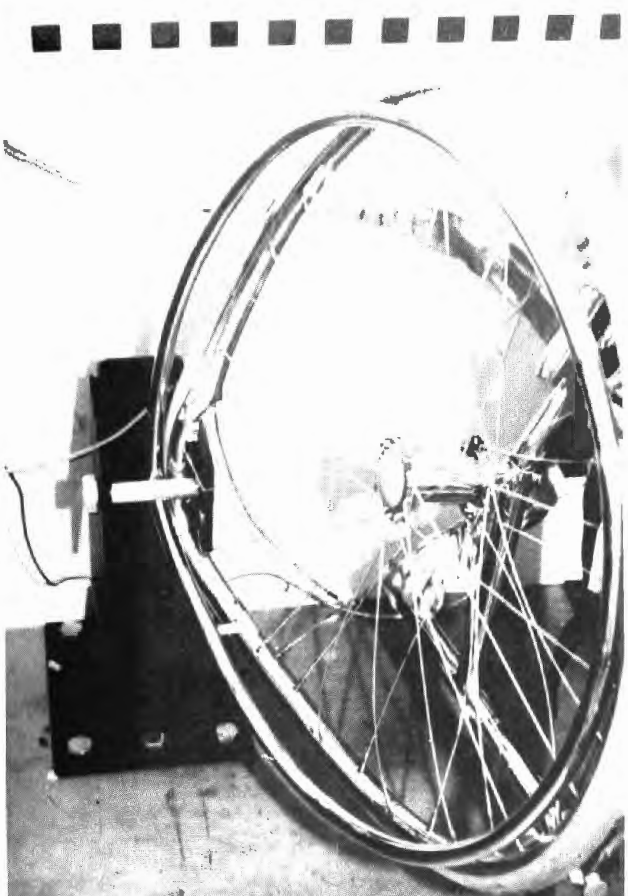
WHEELCHAIR: Major damage resulted to both rear wheels. Figure A-2 shows the damage to the right wheel and Figure A-3 illustrates the damage to the left wheel. The left hub strut yielded, resulting in major damage and severing 50 percent of its diameter above the axle. Minor damage occurred at the right hub strut. The right lower support member was slightly damaged at its joint with the cross brace.

DUMMY: The severe head strike on the armrest resulted in a very high HIC value, 1346. The CSI was 62. Seat belt loads were not available because of damage to the transducer wire during the deceleration period. Head excursion was 49 inches.



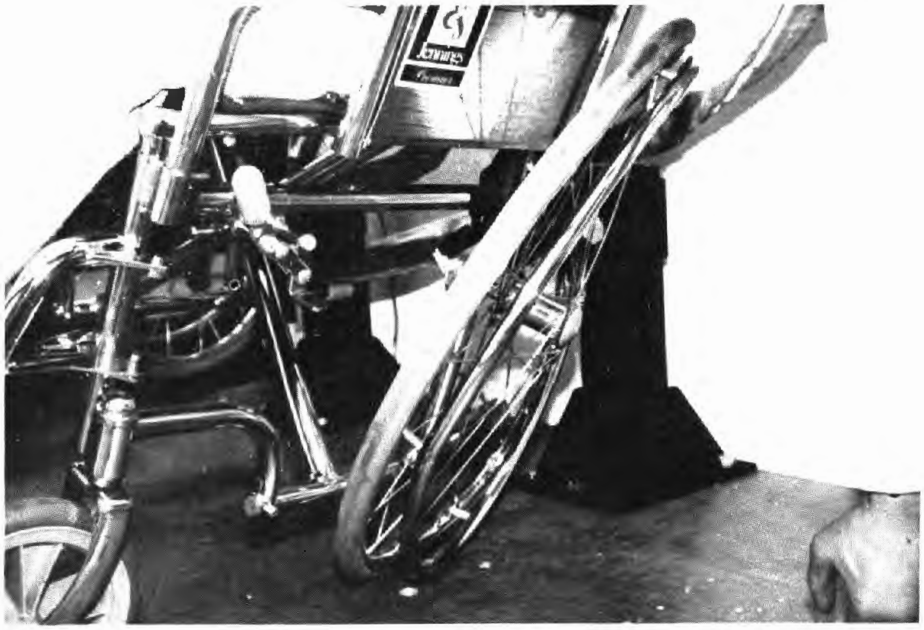
Test 1865 Post-Test Conditions

Figure A-1



Test 1865 Damage - Right Side

Figure A-2



Test 1865 Damage - Left Side

Figure A-3

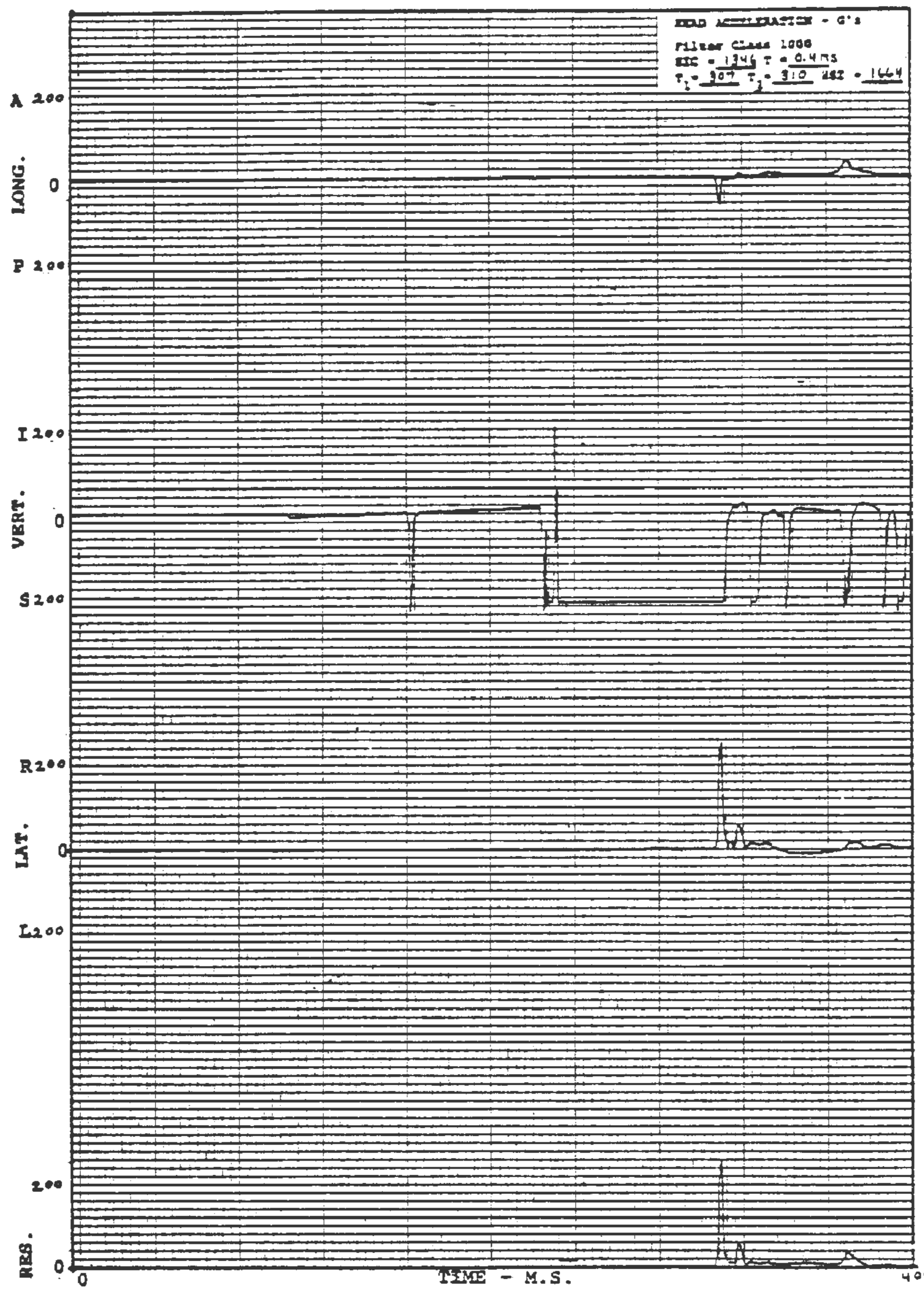


Figure A 4 Head Acceleration Data Traces
Test 1865

TEST NUMBER: 1866 SLED SPEED: 20.3 mph

FACING DIRECTION: Side CRASH PULSE: 4.8 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Floor rim pin

DUMMY: Lap belt to axles

TEST ACTION:

The sideward thrust of the dummy and chair exerted force on the left armrest and caused the chair to rotate and deform. The dummy's head struck the side of its head toward the back on the vertical seat cushion. The head then rotated and struck the steel armrest on the left cheek. The dummy's left hand and right forearm struck the stanchion. The wheelchair leaned about 30 degrees, the dummy's torso leaned about 80 degrees and the wheelchair twisted about 20 degrees to the left during the test. The post-test conditions are illustrated in Figure A-5.

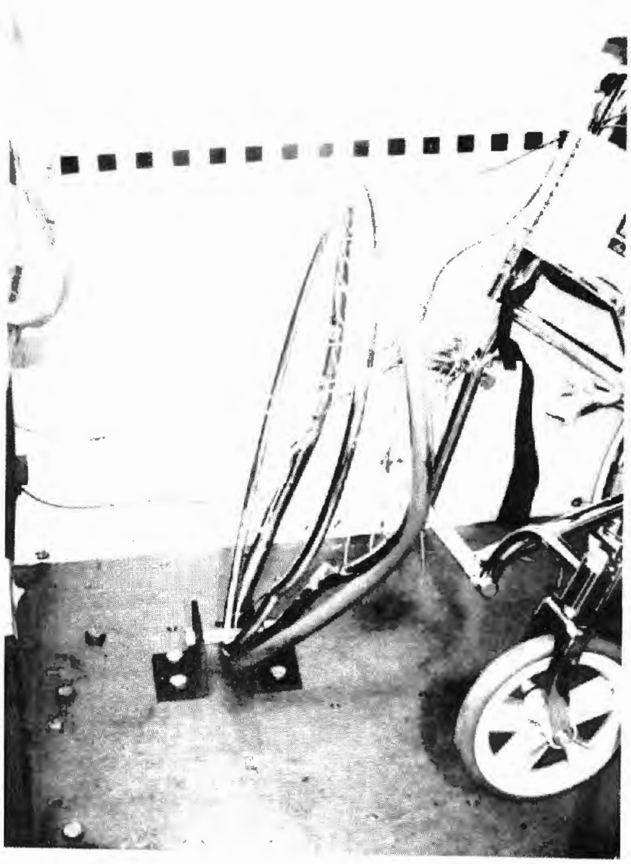
TEST RESULTS:

WHEELCHAIR: The floor rim pin held the wheelchair. The right rear wheel was severely damaged with several spokes separated from the wheel as shown in Figure A-6. The left wheel was folded under severely as shown in Figure A-7. Moderate damage occurred to the left hub strut near the axle.

DUMMY: Recorded head and chest accelerations were low with no particular indication of injury (HIC was 78 and CSI was 28). The head strike on the vertical cushion absorbs enough energy to significantly reduce the HIC value for the strike on the armrest. Belt load was 580 pounds. Head excursion was 48 inches.

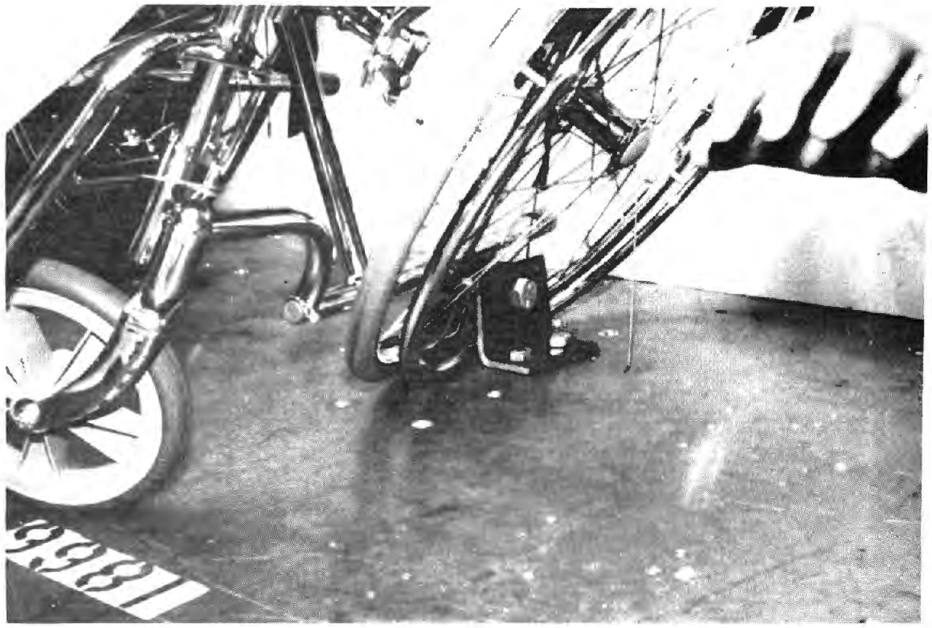
Test 1866 Post-Test Conditions

Figure A-5



Test 1866 Damage - Right Side

Figure A-6



Test 1866 Damage - Left Side

Figure A-7

TEST NUMBER: 1867

FACING DIRECTION: Side

SLED SPEED: 20.3 mph

CRASH PULSE: 5.3 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: User and chair belt

DUMMY: Same belt as chair securement

TEST ACTION:

The chair and occupant tipped about the left wheel, deforming the wheelchair. The back of the dummy's head struck the seat upright cushion and then struck its face on the steel armrest. Its head rotated almost 90 degrees during the two strikes. Its left hand struck the stanchion and steel armrest, and its right hand struck the armrest. The wheelchair leaned about 30 degrees; the dummy's torso leaned about 60 degrees. The wheelchair rotated about 45 degrees to the left. The post-test conditions are illustrated in Figure A-8.

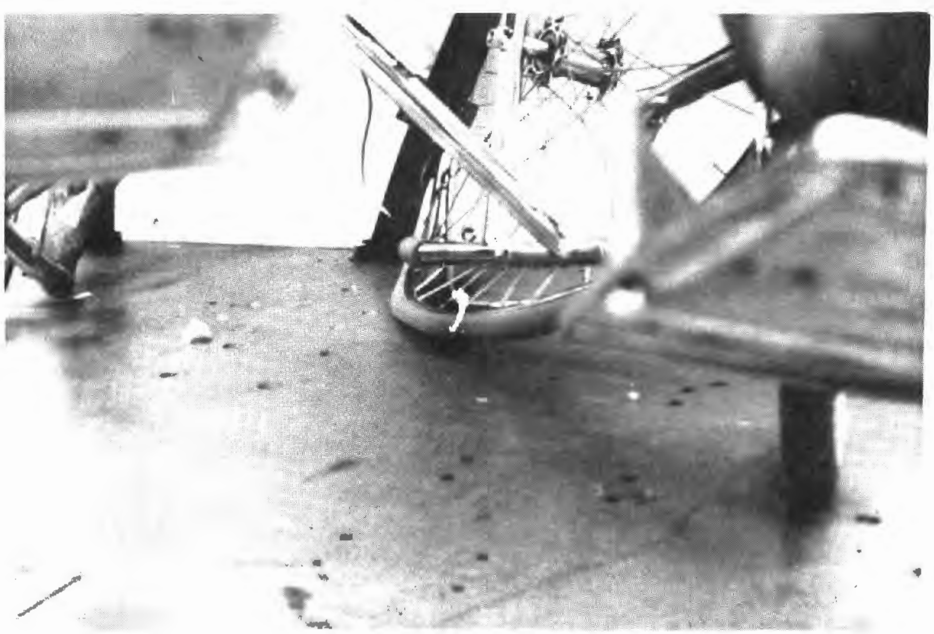
TEST RESULTS:

WHEELCHAIR: Major damage resulted to the right rear wheel as it yielded to conform to the lower support member. The lower support member bent at the joint with the cross strut. The right hub strut yielded above the axle. The left armrest bent at its mounting points. The damage is shown in Figure A-9.

DUMMY: The head and chest accelerations resulted in low HIC and CSI values. The HIC was 174 and the CSI was 44. The head traveled 45 inches during the deceleration period. The belt loads peaked at 1600 pounds.

Test 1867 Post-Test Conditions

Figure A-8



Test 1867 Damage

Figure A-9

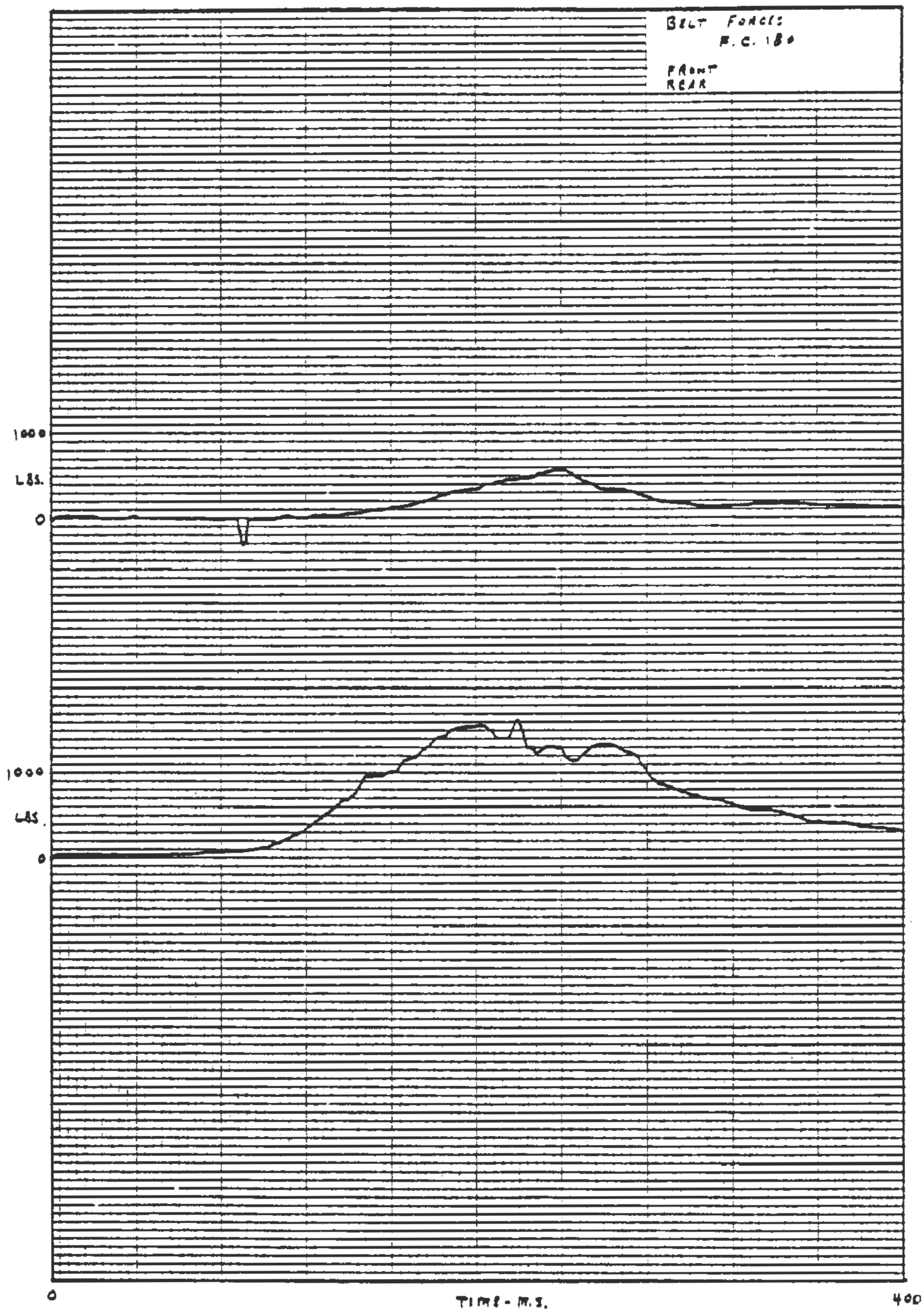


Figure A-10 Lap Belt Force Data Traces
Test 1863

TEST NUMBER: 1868

FACING DIRECTION: Side

SLED SPEED: 21.3 mph

CRASH PULSE: 5.2 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Three-point belt

DUMMY: Lap belt to axles

TEST ACTION:

The chair and occupant tipped in the direction of sled movement. The dummy's left hand struck the steel armrest and then its head hit above the left ear on the foam seat back cushion. The head rotated about 60 degrees but did not strike the steel armrest. The wheelchair leaned about 30 degrees and rotated about 10 degrees to the left; the dummy's torso leaned about 60 degrees.

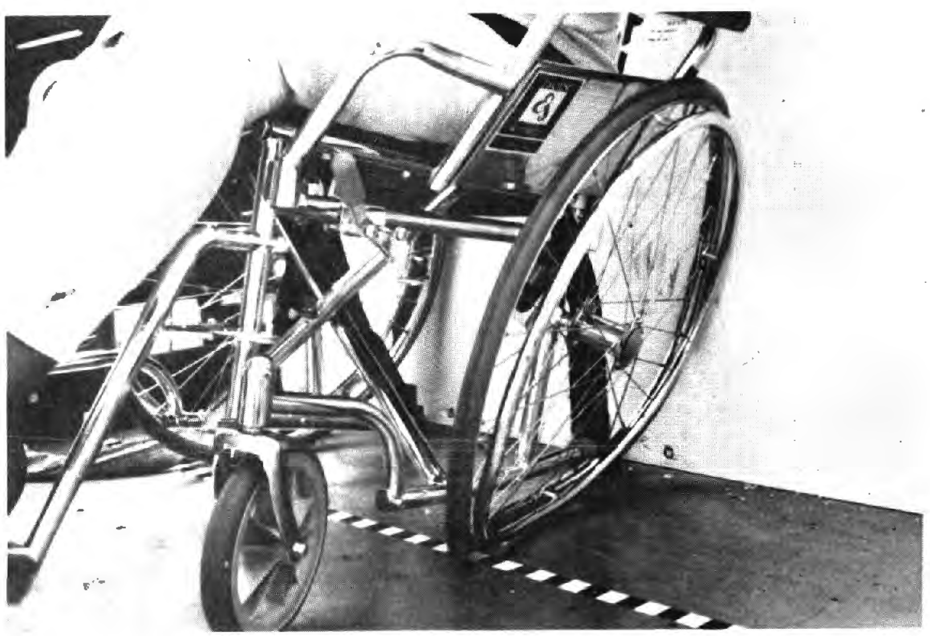
TEST RESULTS:

WHEELCHAIR: The left wheel was moderately deformed and the left armrest was severely bent, as shown in Figure A-11. Figure A-12 presents the left wheel damage from another perspective. The left lower support member bent at its connection with the cross brace. The left hub strut split over about 25 percent of its diameter below the axle support. In general, the entire frame was damaged at least mildly.

DUMMY: Both dummy acceleration measurements were low resulting in a HIC of 50 and a CSI of 34. The head excursion was 45 inches. The peak belt load was 300 pounds.

Test 1868 Damage - Left Side

Figure A-11



Test 1868 Damage - Underneath

Figure A-12

TEST NUMBER: 1880 | SLED SPEED: 21.9 mph

FACING DIRECTION: Forward | CRASH PULSE: 9.5 g's

CHAIR TYPE: Electric

SECUREMENT

WHEELCHAIR: Three-point belt

DUMMY: Lap belt to axles

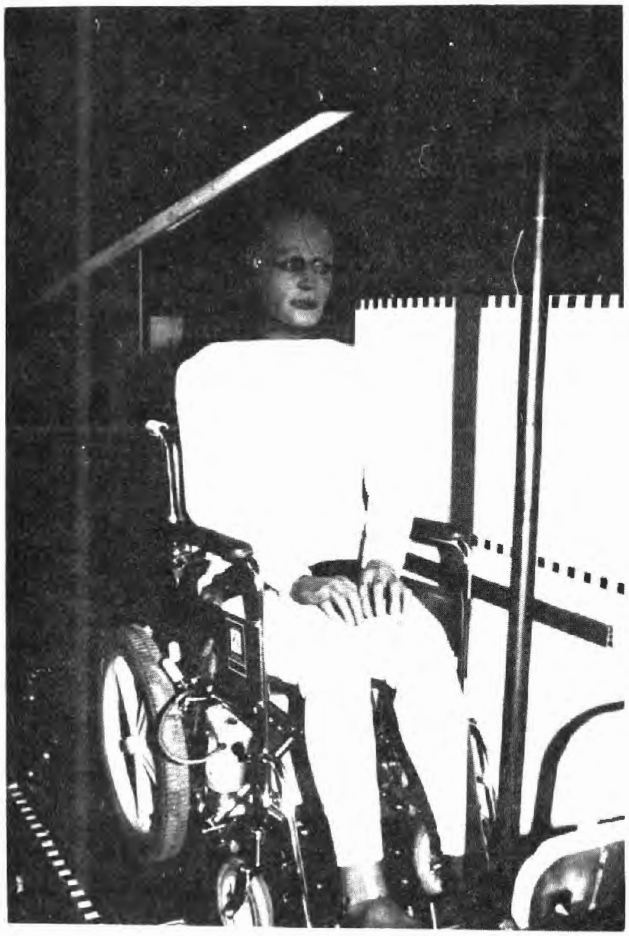
TEST ACTION:

As the sled was decelerating, the dummy slid forward from the wheelchair and jackknifed about his waist and lifted up from the seat. The wheelchair moved forward only slightly during deceleration. The dummy's torso leaned forward about 80 degrees. The dummy's right hand hit the seat armrest and the left hand hit the vertical back cushion. Then the dummy's forehead struck the steel armrest. The battery box detached from the rear of the wheelchair. See Figures A-14 and A-16.

TEST RESULTS:

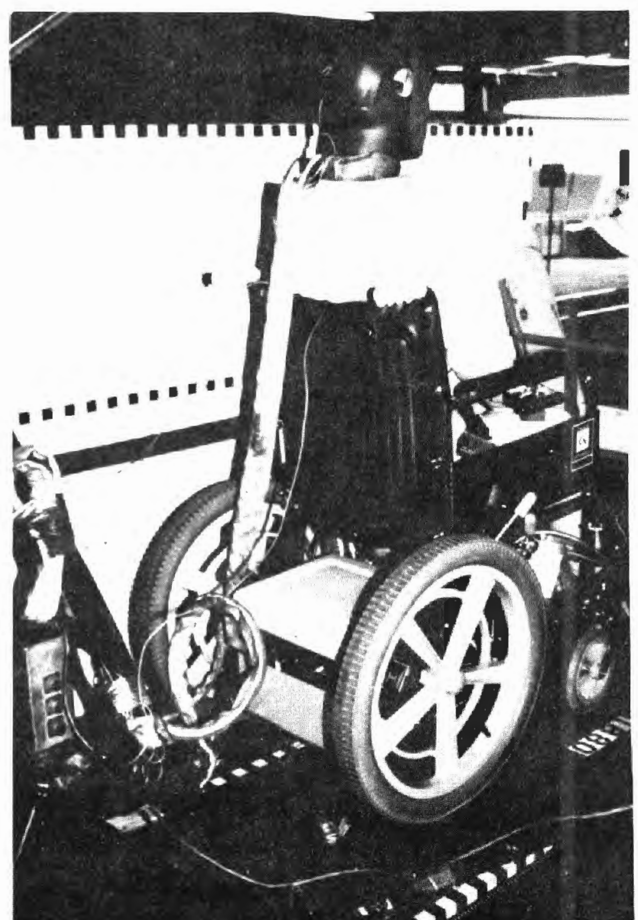
WHEELCHAIR: Moderate damage resulted when both the right and left hub struts yielded at their points of contact with the rear restraint belts. The left armrest assembly was bent slightly outward, and the battery box mounting brackets were deformed. The battery and battery box were undamaged.

DUMMY: The severe forehead strike resulted in a large HIC of 2078. The CSI was 156, and the seat belt loads were 920 pounds. Head excursion was 41 inches.



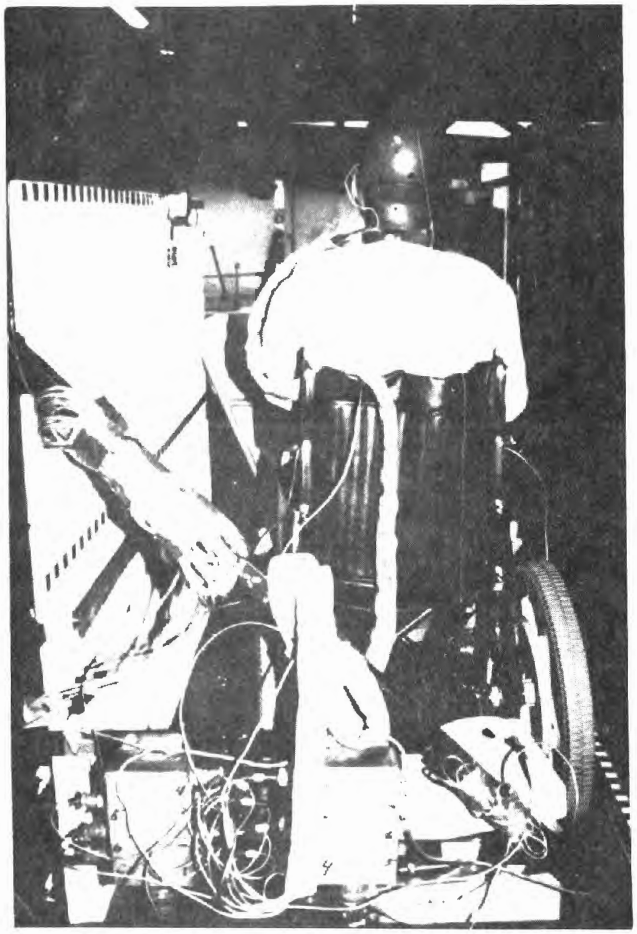
Test 1880 Test Configuration

Figure A-13



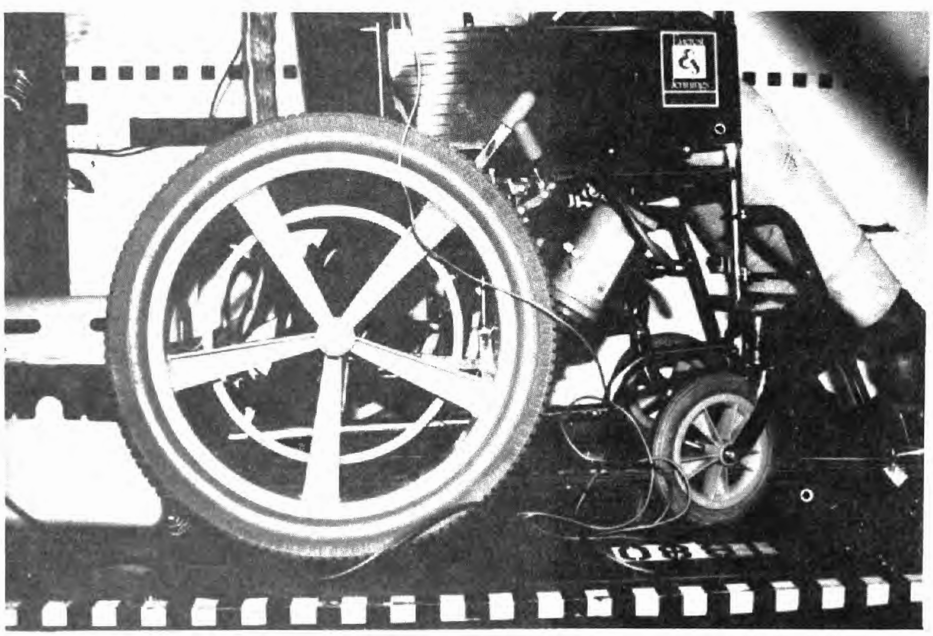
Test 1880 Post-Test Conditions

Figure A-14



Test 1880 Damage - Rear Upper

Figure A-15



Test 1880 Damage - Rear Lower

Figure A-16

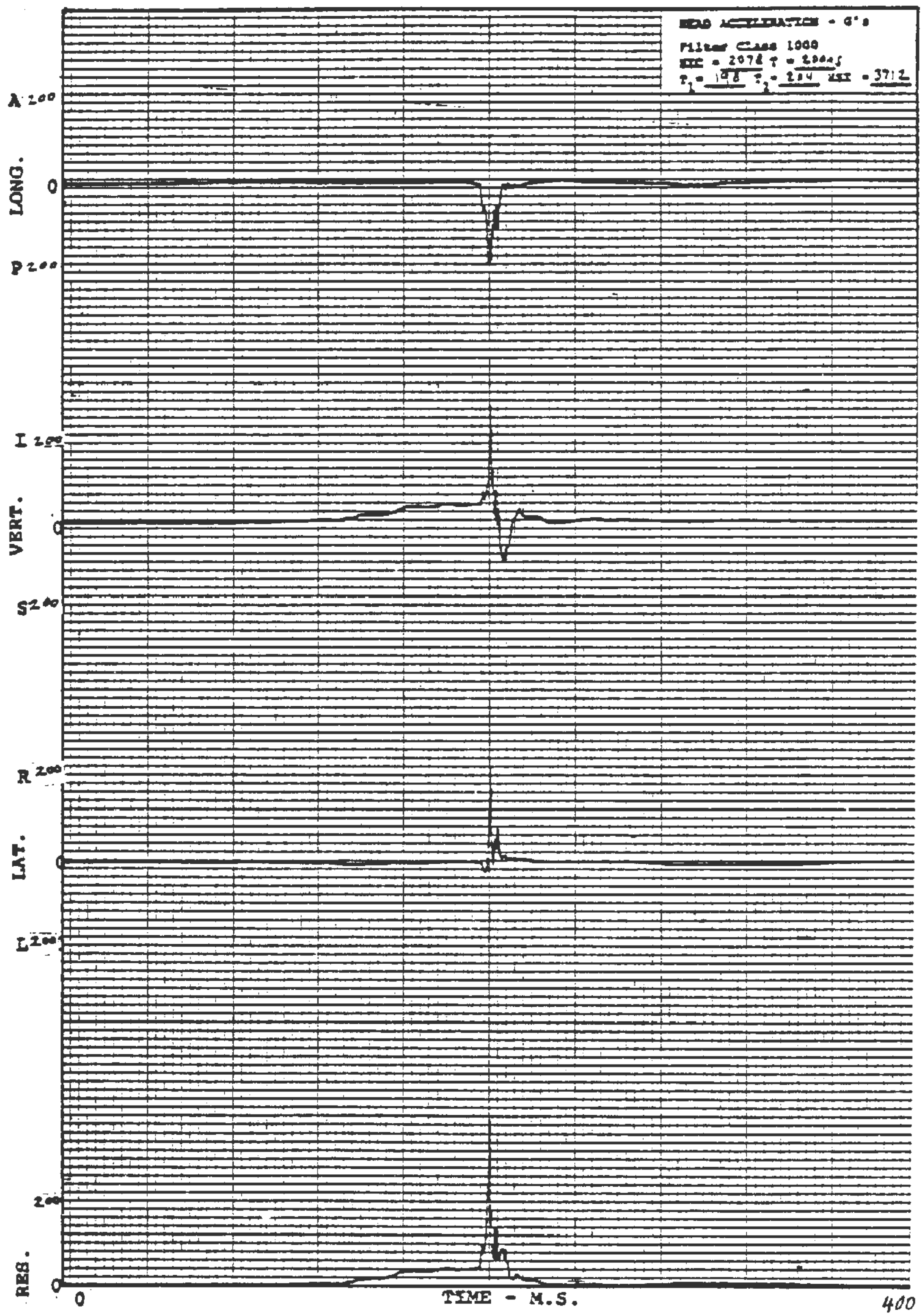
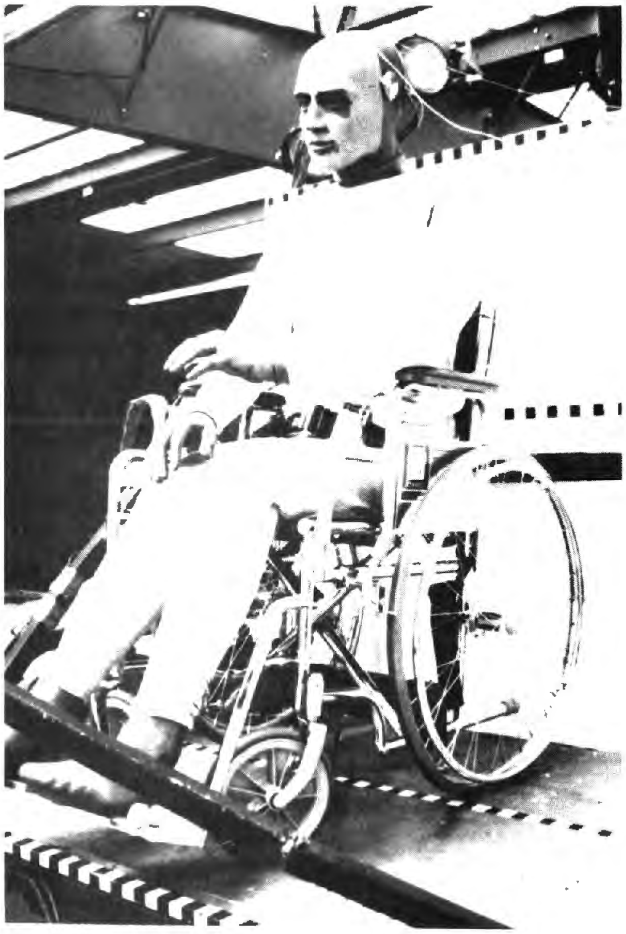


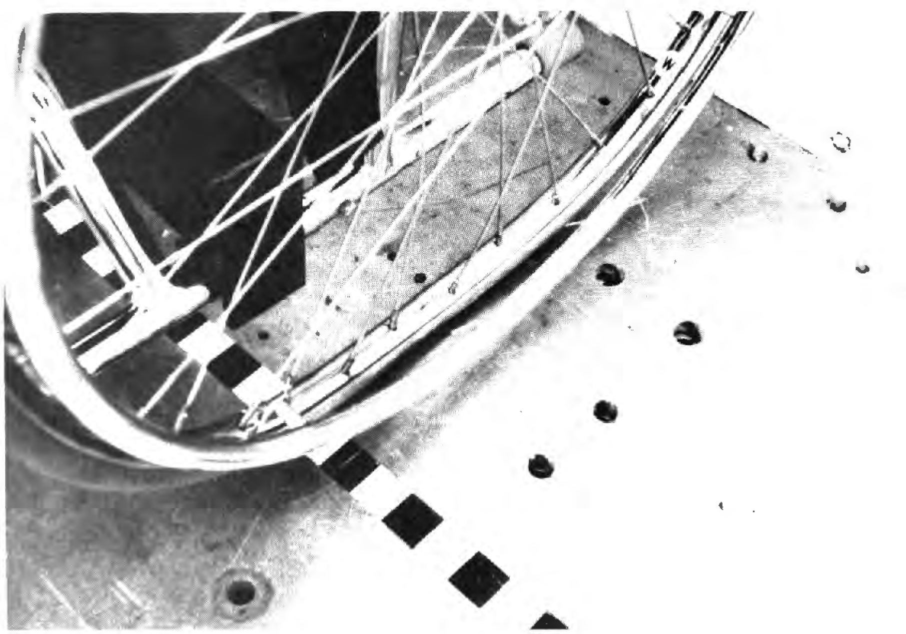
Figure A-17 Head Acceleration Data Traces

Test 1880



Test 1876 Post-Test Conditions

Figure A-18



Test 1876 Damage - Left Wheel Showing T-Bar

Figure A-19

TEST NUMBER: 1876

FACING DIRECTION: Side

SLED SPEED: 10.9 mph

CRASH PULSE: 5.0 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Rear T-bar

DUMMY: Lap belt to axles

TEST ACTION:

The system proved effective at the reduced velocity and deceleration levels. The wheelchair leaned about 10 degrees and was restrained from further movement. The dummy's torso leaned about 45 degrees. There were no head, hand or arm strikes.

TEST RESULTS:

WHEELCHAIR: The left rear wheel sustained minor damage.

DUMMY: The HIC was 10, the CSI was 0, and the peak lap belt loads were 120 pounds. The head excursion measured 26 inches.

TEST NUMBER: 1882

SLED SPEED: 10.1 mph

FACING DIRECTION: Forward

CRASH PULSE: 4.3 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Single rim latch

DUMMY: Lap belt to axles

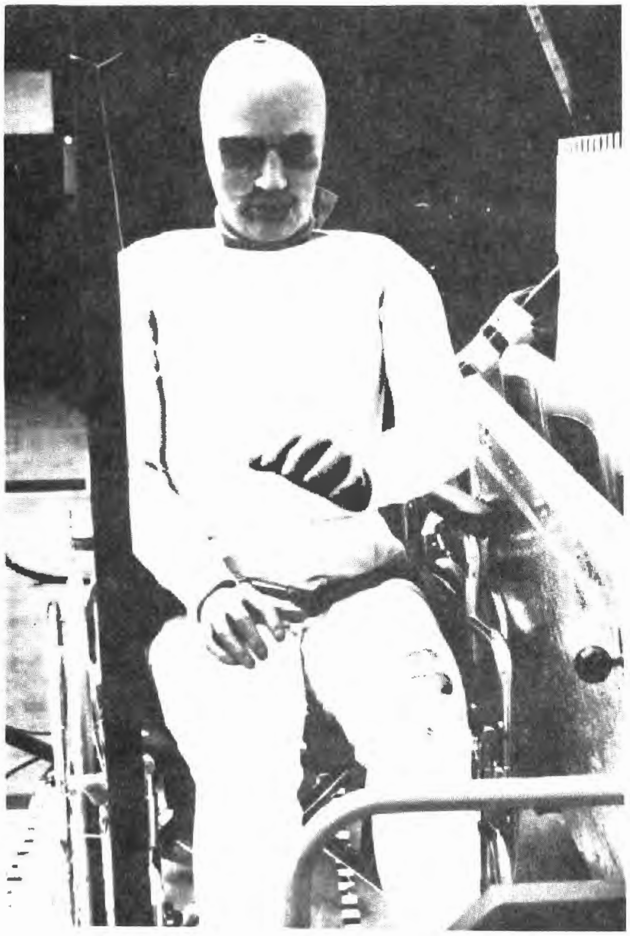
TEST ACTION:

With the reduced speed and crash pulse, the wheelchair and occupant realized only minor movement with no head, hand or arm strikes. The chair twisted left about 20 degrees while the body pitched forward about 45 degrees. This securement system held and the strain gauges attached to both sides of the latch recorded a peak force of 550 pounds.

TEST RESULTS:

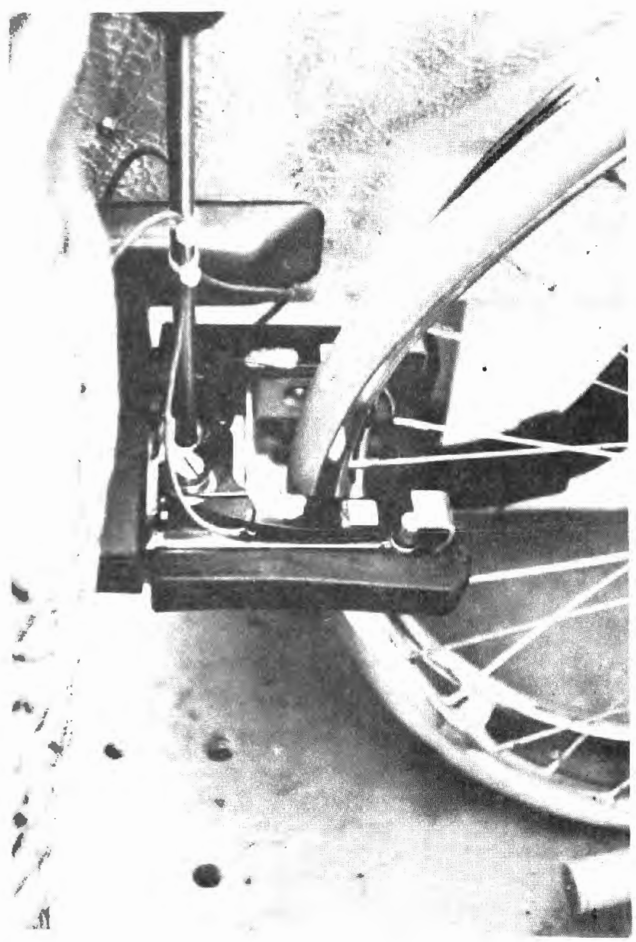
WHEELCHAIR: Moderate damage resulted to the left rear wheel at its point of contact with the wheel clamp. The wheel was distorted and a few spokes were detached. The damage is shown in Figures A-21 and A-22. The lower support member was bent.

DUMMY: Since there was no dummy strike, the HIC was 4 and the CSI was 0. The head excursion was 35 inches and the peak belt load measured was 300 pounds.



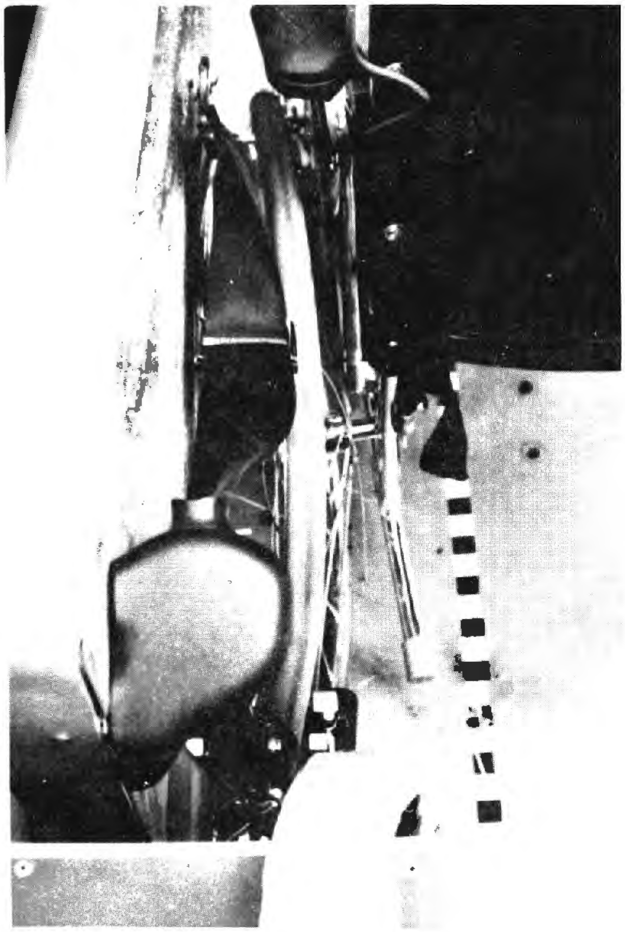
Test 1882 Post-Test Condition

Figure A-20



Test 1882 Damage - Left Wheel
Showing Clamp

Figure A-21



Test 1882 Damage - Left Side

Figure A-22

TEST NUMBER: 1967 SLED SPEED: 20.8 mph

FACING DIRECTION: Forward CRASH PULSE: 5.0 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Single rim latch

DUMMY: Lap belt to axles

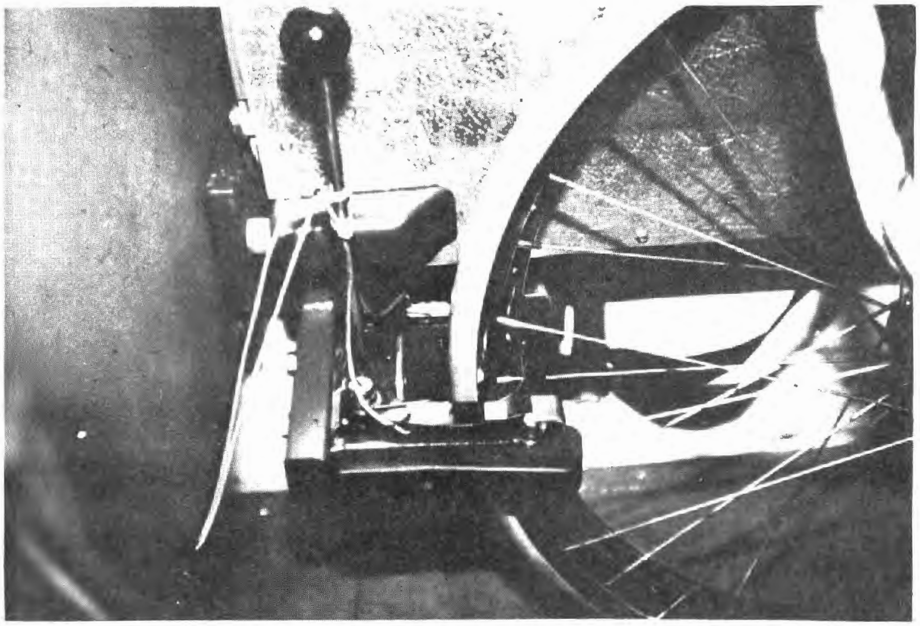
TEST ACTION:

As the sled decelerated, the chair and dummy continued their forward movement. The left wheel lifted, twisted, and several of the spokes ripped out of the rim. The dummy jackknifed and was thrust forward but the movement became restricted when the right shoulder hit the stanchion. The dummy rebounded to the position seen in Figure A-25.

TEST RESULTS:

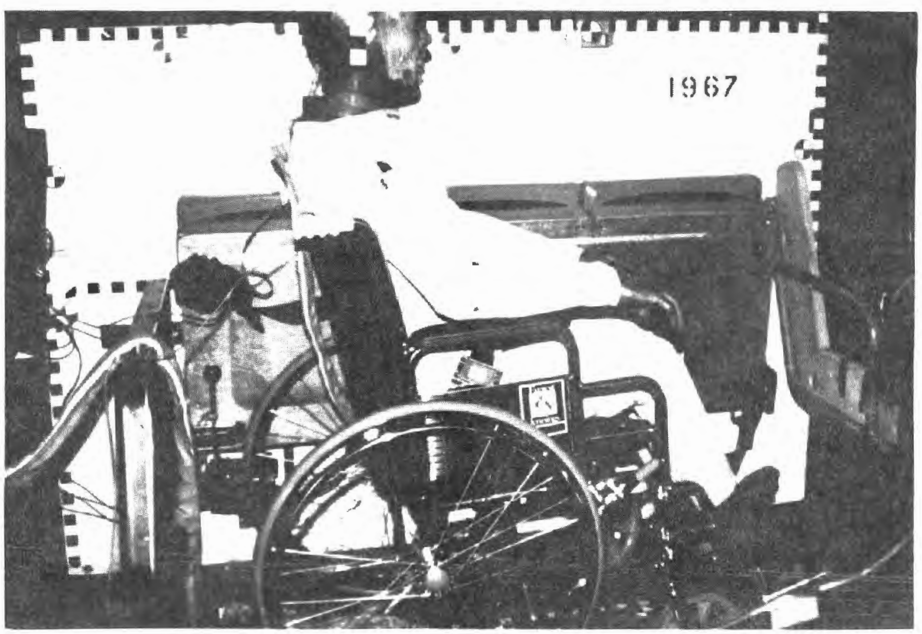
WHEELCHAIR: The left rear wheel collapsed. The spokes were broken and the rim was severely bent as shown in Figure A-26. The left axle strut was slightly bent. The off-the-shelf, manufacturer strengthened securement held. The rim latch strain gauges peaked at 720 pounds.

DUMMY: The dummy suffered a shoulder strike. Although the test films show the shoulder strike to be quite severe, the head and chest accelerometers did not appear to be significantly affected by it. The HIC was 78 and the CSI was 62. The head excursion measured 52 inches. The peak belt load was 480 pounds.



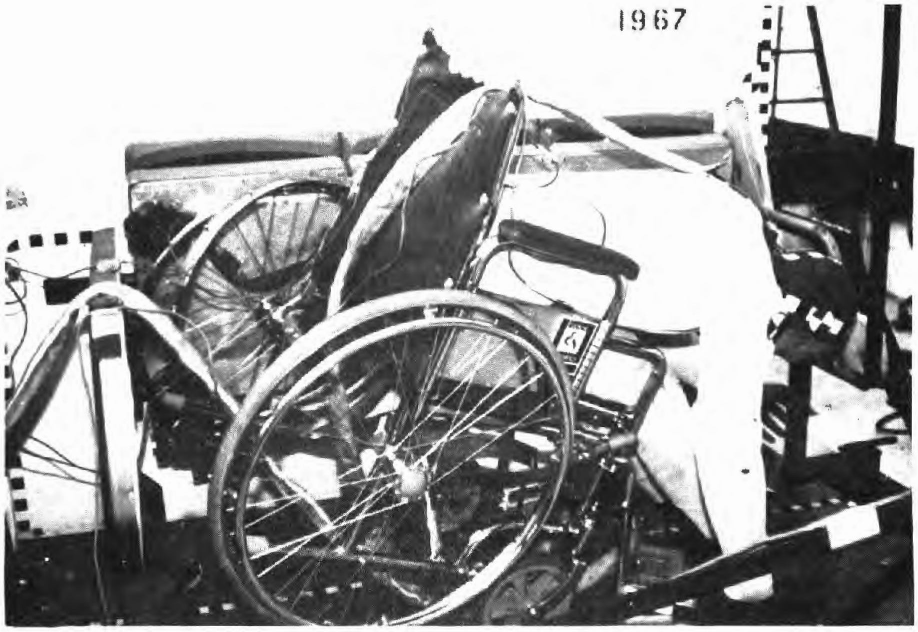
Test 1967 Single Rim Latch

Figure A-23



Test 1967 Test Configuration

Figure A-24



Test 1967 Post-Test Condition

Figure A-25

Test 1967 Left Wheel Damage

Figure A-26

TABLE A-1 EXCURSION, TEST 1967

Single Rim Latch
Forward Facing Manual Wheelchair (S/N 1812237)
20 mph, 5 Gs
7 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	11.75	17	22
Rear axle to rear of sled	28.5	26	21.5
Front axle to floor	3.75	3.75	5
Front axle to rear of sled	48	36	35
Knee point to floor	23	18	15
Knee point to rear of sled	46	47	45.5
Head point to overhead camera*	15		
Head point to floor**	48	22	
Head point to on-board side camera*	47		
Head point to rear of sled**	25	57.5	
Ankle point to floor	9	4	3
Ankle point to rear of sled	54	54.5	54
Wheelchair front axle to edge of sled	8.5		
Wheelchair rear axle to edge of sled	7		
Shoulder to floor	38	25	27
Shoulder to rear of sled	26	49	51

*Measured to head bolt.

**Measured to target.

TEST NUMBER: 1968

FACING DIRECTION: Forward

SLED SPEED: 19.8 mph

CRASH PULSE: 4.8 g's

CHAIR TYPE: Electric

SECUREMENT

WHEELCHAIR: Single rim latch

DUMMY: Lap belt to axles

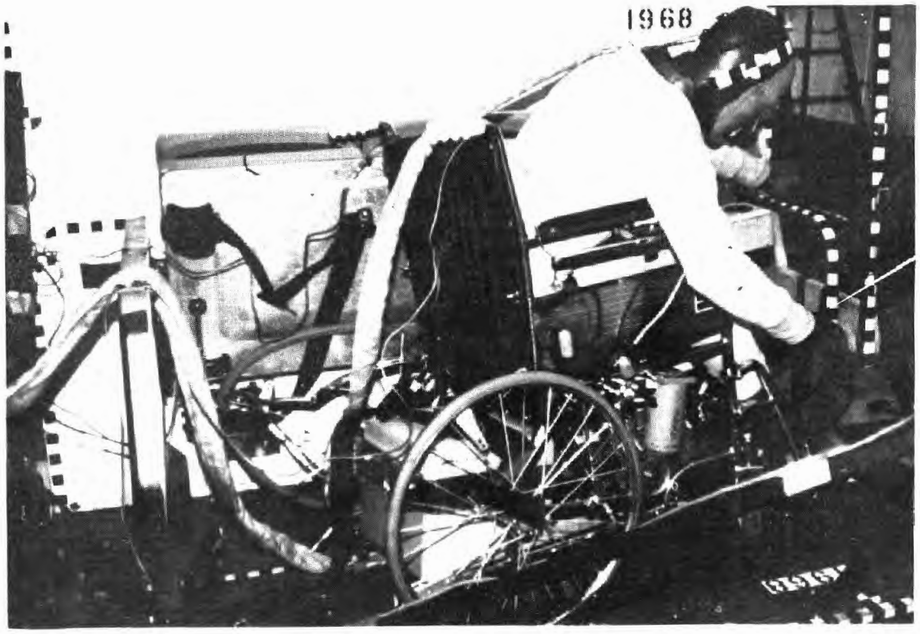
TEST ACTION:

The left wheel was greatly elongated, breaking many of its spokes. The dummy pitched forward, bending at the waist. The right shoulder violently struck the stanchion.

TEST RESULTS:

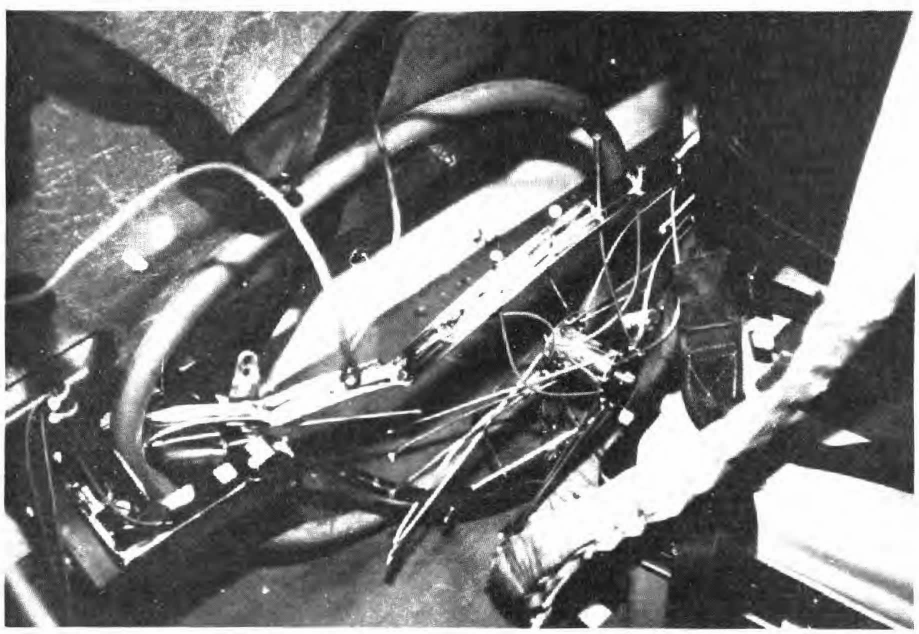
WHEELCHAIR: The left wheel failed completely. There was minimal damage to the frame. The securement held. Maximum latch load recorded on the strain gauge was 1450 pounds, about twice the load experienced in test 1967 using a manual wheelchair.

DUMMY: The HIC was 150 and the CSI was 129. The peak lap belt load was 150 pounds. The right shoulder strike on the stanchion was the only strike the dummy experienced. Head excursion was 54 inches.



Test 1968 Post-Test Condition

Figure A-27



Test 1968 Close-Up of Wheel Damage

Figure A-28

TABLE A-2 EXCURSION, TEST 1968

Single Rim Latch
Forward Facing Electric Wheelchair (S/N 1825036)
20 mph, 5 Gs
8 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	10	10	8.5
Rear axle to rear of sled	26.5	34.5	30
Front axle to floor	3.75	3.75	3.75
Front axle to rear of sled	50	57	53.5
Knee point to floor	24	22.5	22.5
Knee point to rear of sled	48.5	52	51.5
Head point to overhead camera*	10		
Head point to floor**	50	39.5	
Head point to on-board side camera*	45.5		
Head point to rear of sled**	32	55	
Ankle point to floor	9	9	9.5
Ankle point to rear of sled	54.5	61	61.5
Wheelchair front axle to edge of sled	9	11.5	
Wheelchair rear axle to edge of sled	7	4.5	
Shoulder to floor	41.5	36	36.5
Shoulder to rear of sled	30.5	45.5	47

*Measured to head bolt.

**Measured to target.

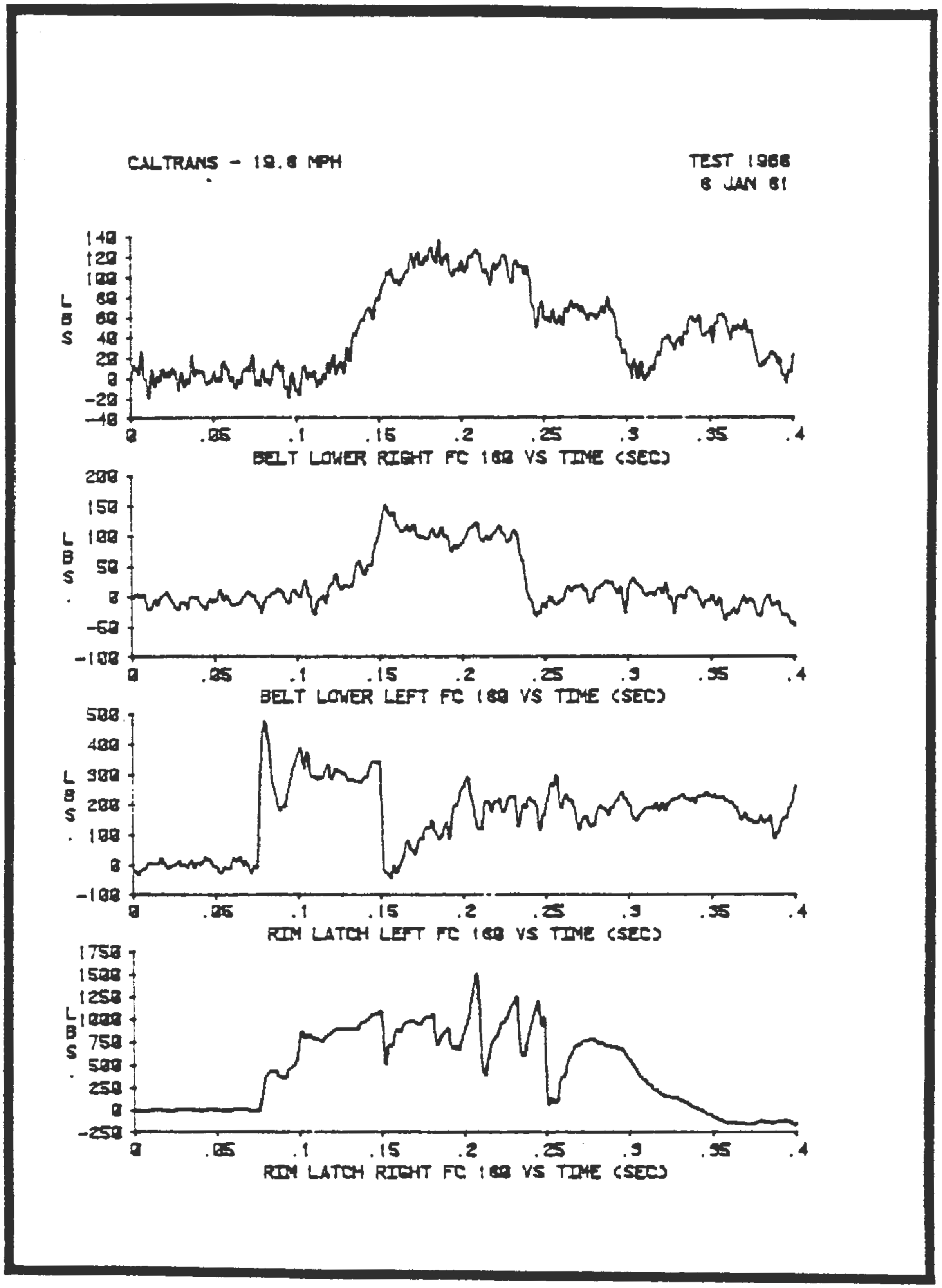


FIGURE A-29 BELT AND RIM LATCH FORCES, TEST 1968

TEST NUMBER: 1966 | SLED SPEED: 20.2 mph

FACING DIRECTION: Forward | CRASH PULSE: 4.9 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Single rim latch with three point belt occupant restraint

DUMMY: Same belt as wheelchair

TEST ACTION:

Very minimal forward movement of wheelchair and occupant occurred. Table A-3 shows the amount of wheelchair and dummy movement with respect to their location at impact. The right arm and right foot swung forward. No strikes occurred with the sled structure.

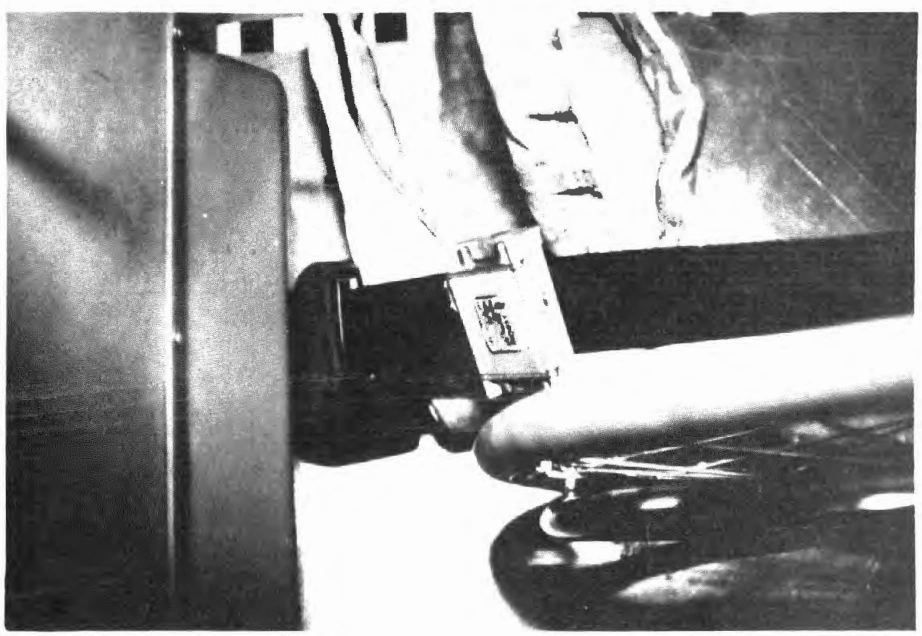
TEST RESULTS:

WHEELCHAIR: Damage to the wheelchair was minimal. The left rim had a small dent where it contacted the rim latch.

DUMMY: The HIC was 22 and the CSI was 24, minimal values indicating small head and chest accelerations. The peak rim latch force was 560 pounds. The instrumentation for the upper left belt (shoulder) failed. A comparison of the lower right and left lap belt forces revealed the lower right lap belt had the higher force level of 590 pounds. Head excursion was 12 inches.

Test 1966 Rear View of
Upper Torso Belt

Figure A-30

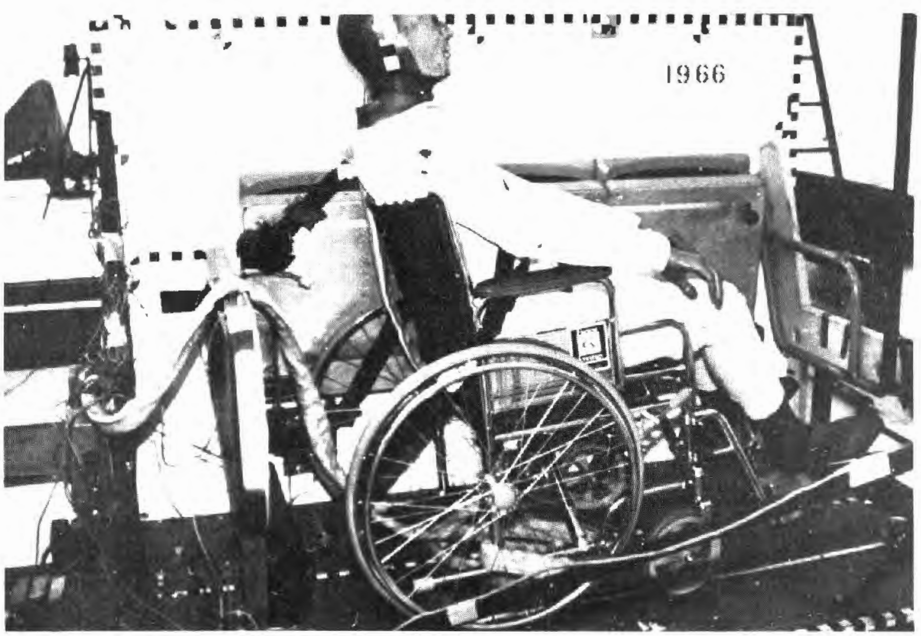


Test 1966 Floor Mounted Retractor

Figure A-31

Test 1966 Seating Position

Figure A-32



Test 1966 Post-Test Condition

Figure A-33

TABLE A-3 EXCURSION, TEST 1966

Upper Torso Belt Restraint with Single Rim Latch
Forward Facing Manual Wheelchair (S/N 1812237)
20 mph, 5 Gs
6 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	11.75	11.75	11.75
Rear axle to rear of sled	27	28.5	28
Front axle to floor	3.75	4	4
Front axle to rear of sled	46.5	44.5	44
Knee point to floor	23	23.5	25
Knee point to rear of sled	46	48.5	50
Head point to overhead camera*	17		
Head point to floor**	48	46.5	
Head point to on-board side camera*	48.5		
Head point to rear of sled**	23	22.5	
Ankle point to floor	8	10.5	11
Ankle point to rear of sled	52	58	58
Wheelchair front axle to edge of sled	6.5	8	
Wheelchair rear axle to edge of sled	6	6.5	
Shoulder to floor	38	37	36
Shoulder to rear of sled	25	24.5	28

*Measured to head bolt.

**Measured to target.

TEST NUMBER: 1884 | SLED SPEED: 19.6 mph

FACING DIRECTION: Side | CRASH PULSE: 9.4 g's

CHAIR TYPE: Electric

<u>SECUREMENT</u>

WHEELCHAIR: Frame anchor

DUMMY: Lap belt to axles

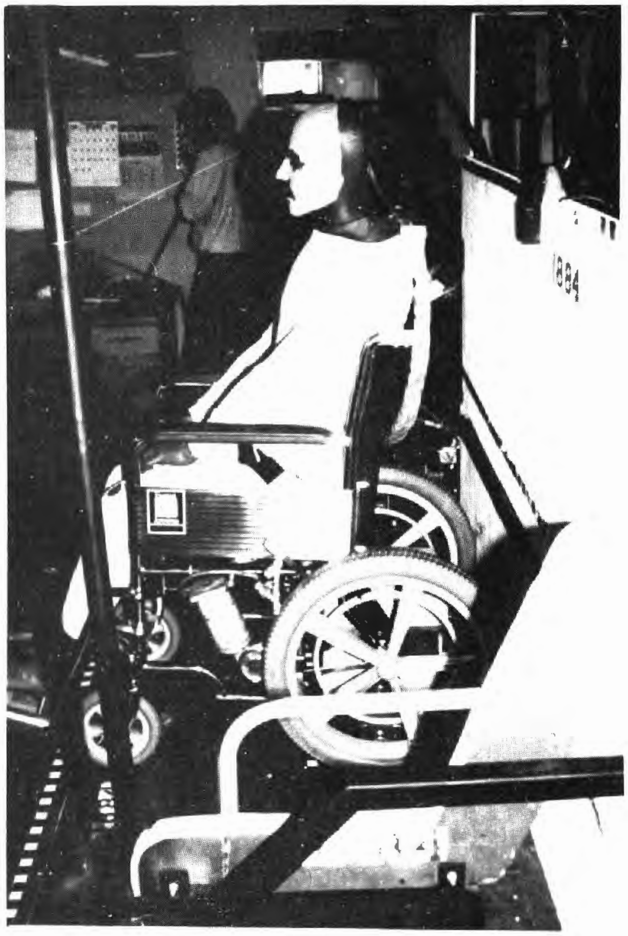
<u>TEST ACTION</u>:

The dummy leaned severely over the wheelchair's left armrest, his head just missing the sled armrest. The dummy's left arm swung out and his head hit the left elbow. While the wheelchair tipped about its left side, the frame bent in the direction of travel.

<u>TEST RESULTS</u>:

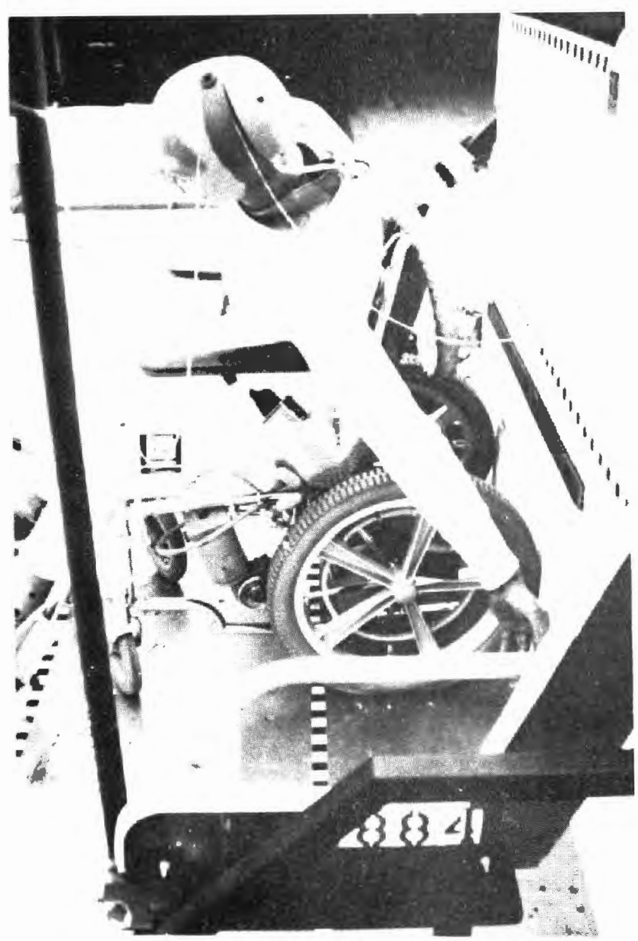
WHEELCHAIR: The wheelchair was held securely by this securement but the dummy leaned a great distance. Moderate to major damage occurred at several places in the wheelchair frame. Right side damage is shown in Figure A-36.

DUMMY: The head strike on the left elbow resulted in a HIC of 472. There was minor chest acceleration, the CSI was 34. Peak belt load was 900 pounds. Head excursion was 41 inches.



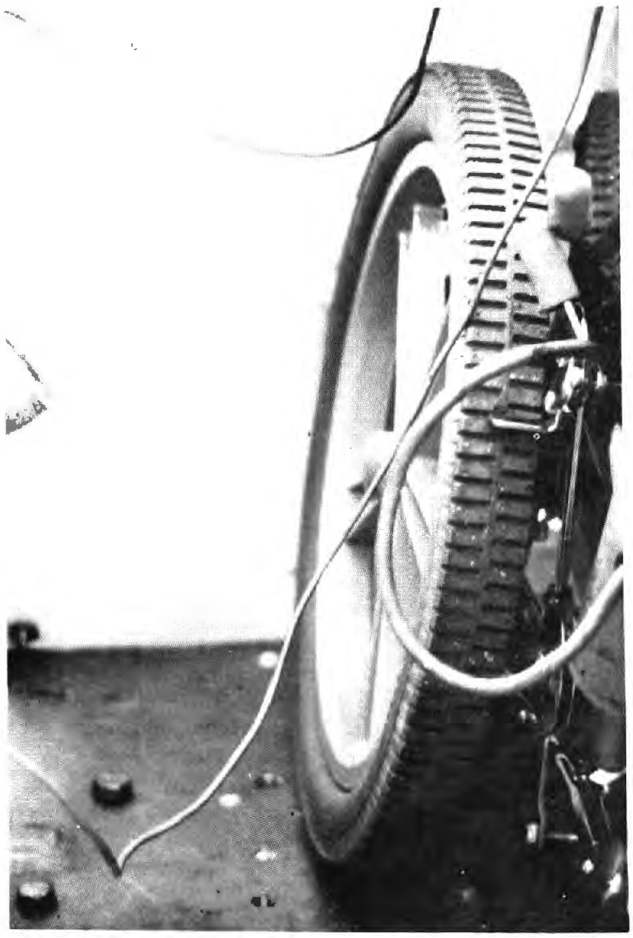
Test 1884 Test Configuration

Figure A-34



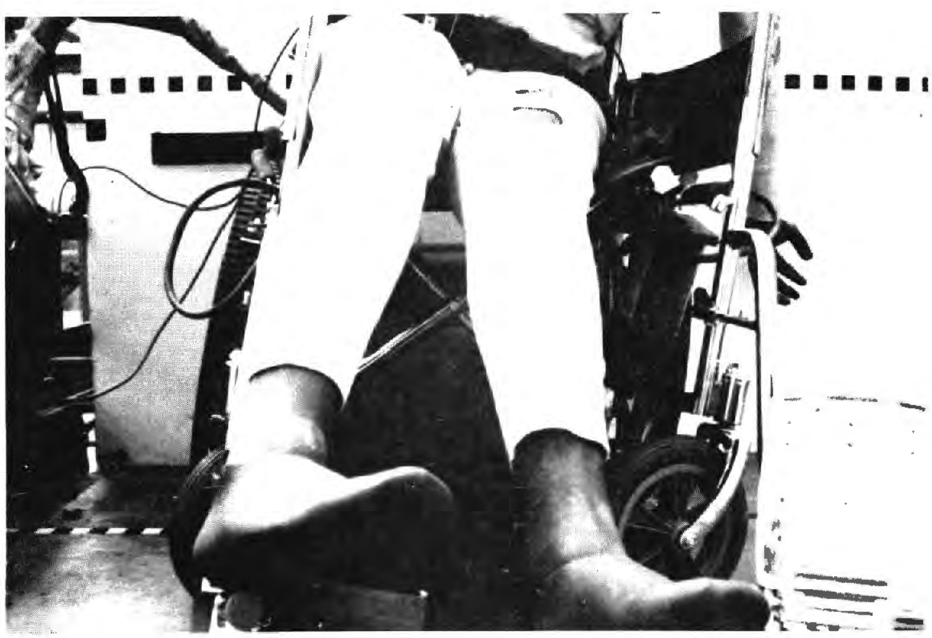
Test 1884 Post-Test Conditions

Figure A-35



Test 1884 Damage - Right Side

Figure A-36



Test 1884 Damage - Left Side

Figure A-37

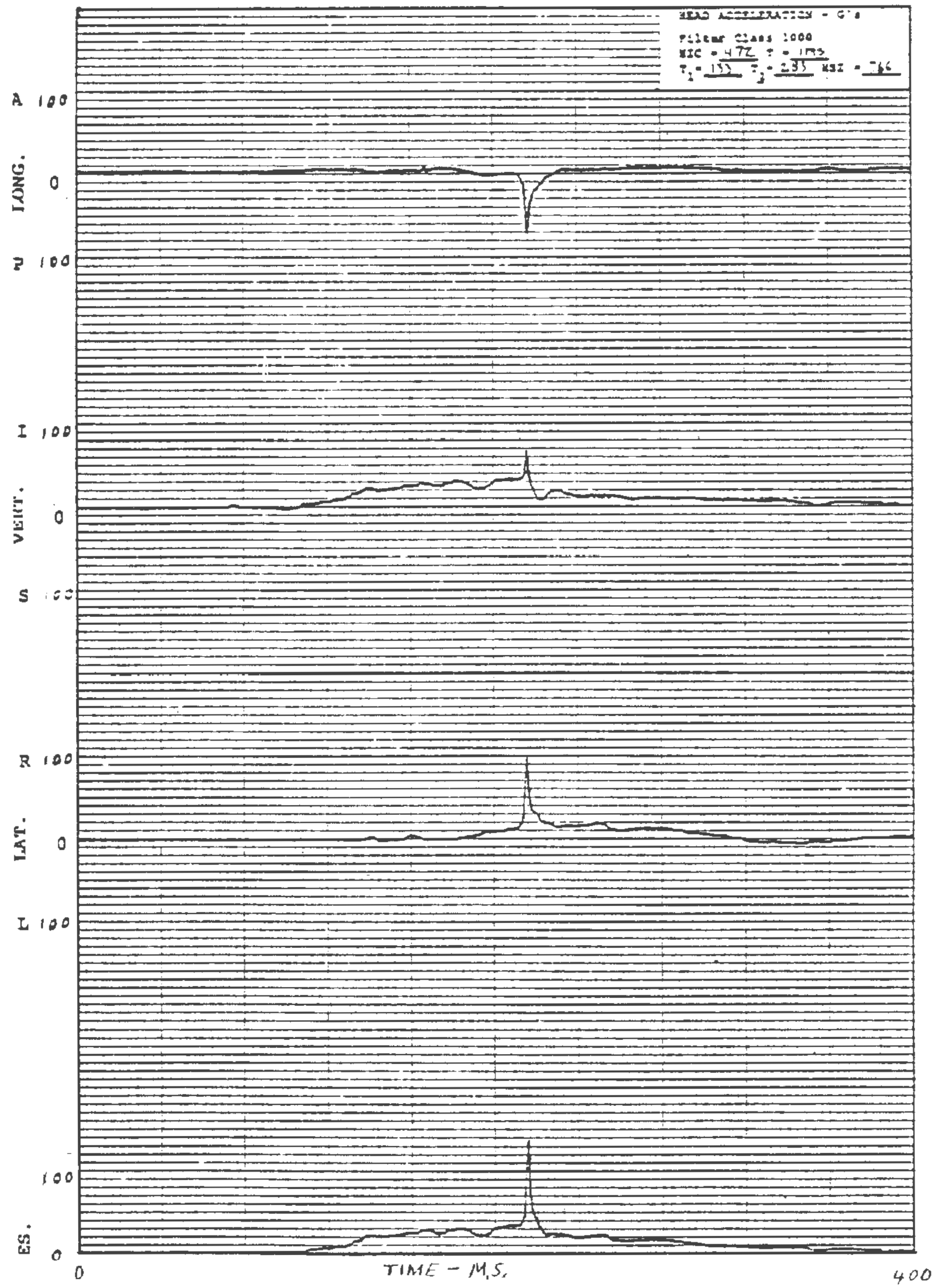


Figure A-38 Head Acceleration Data Traces

Test 1884

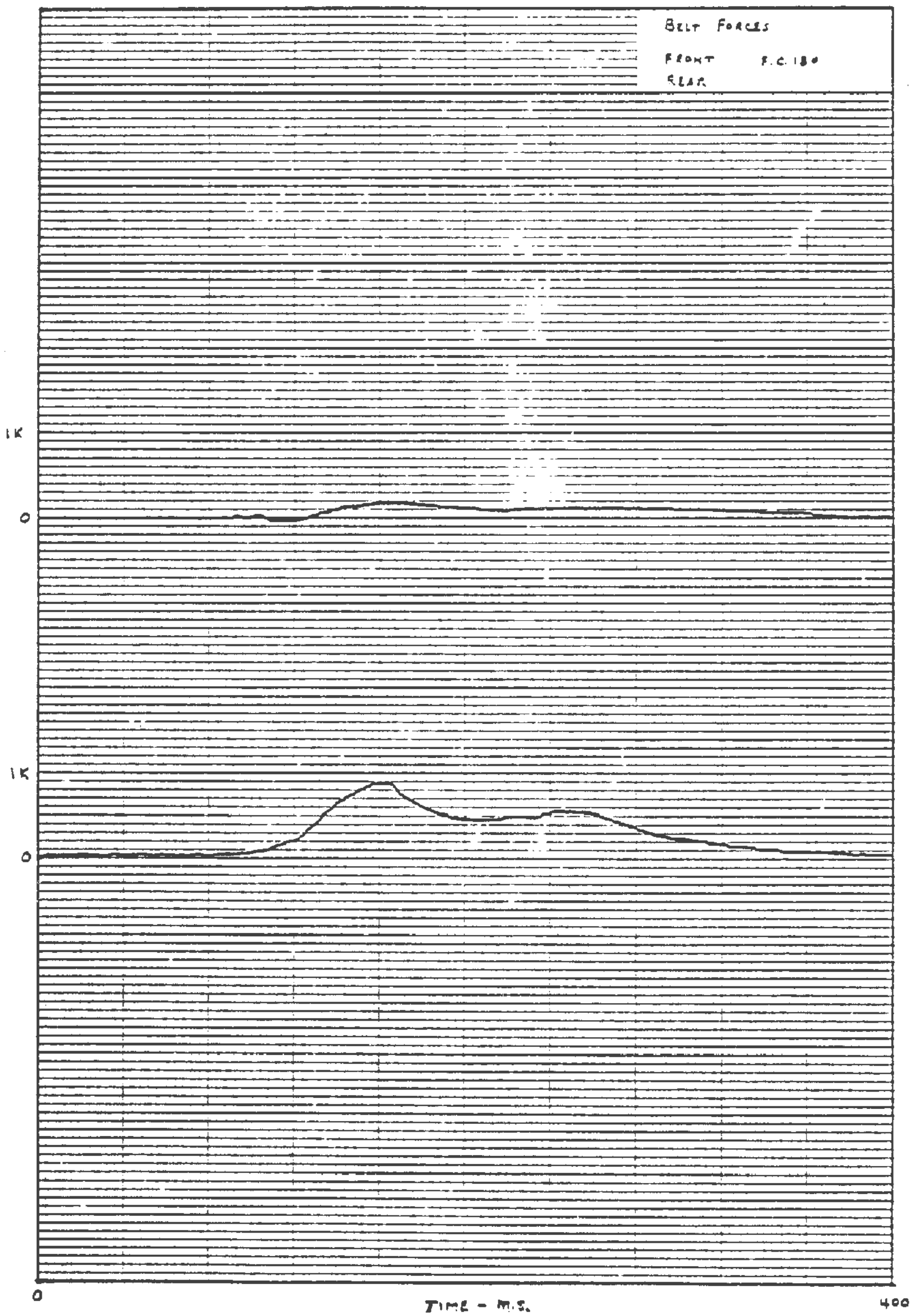


Figure A-39 Lap Belt Force Data Traces

Test 1884

TEST NUMBER: 1885 SLED SPEED: 10.6 mph

FACING DIRECTION: Side CRASH PULSE: 4.8 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Horizontal bars

DUMMY: Lap belt to axles

TEST ACTION:

The dummy's torso leaned about 25 degrees to the left and the wheelchair leaned about 20 degrees. No strikes occurred.

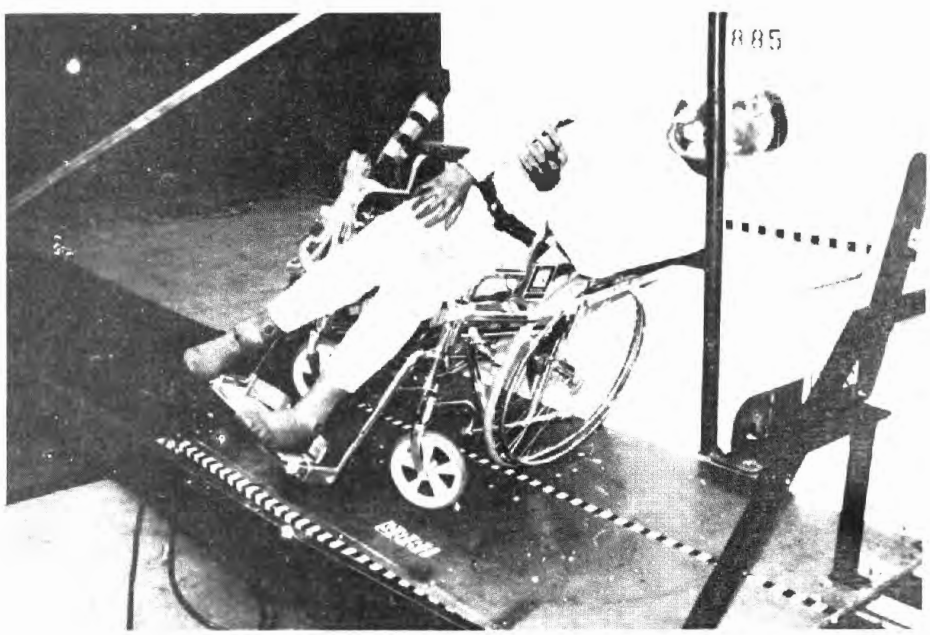
TEST RESULTS:

WHEELCHAIR: The left wheel rim was slightly bent as shown in Figure A-41.

DUMMY: The HIC was 4, CSI was 0, head excursion was 35 inches, and maximum belt load was 100 pounds.

Test 1885 Test Configuration

Figure A-40



Test 1885 Damage - Left Side

Figure A-41

TEST NUMBER: 1887

FACING DIRECTION: Forward

SLED SPEED: 20.3 mph

CRASH PULSE: 9.3 g's

CHAIR TYPE: Electric

SECUREMENT

WHEELCHAIR: Frame anchor

DUMMY: Lap belt to axles

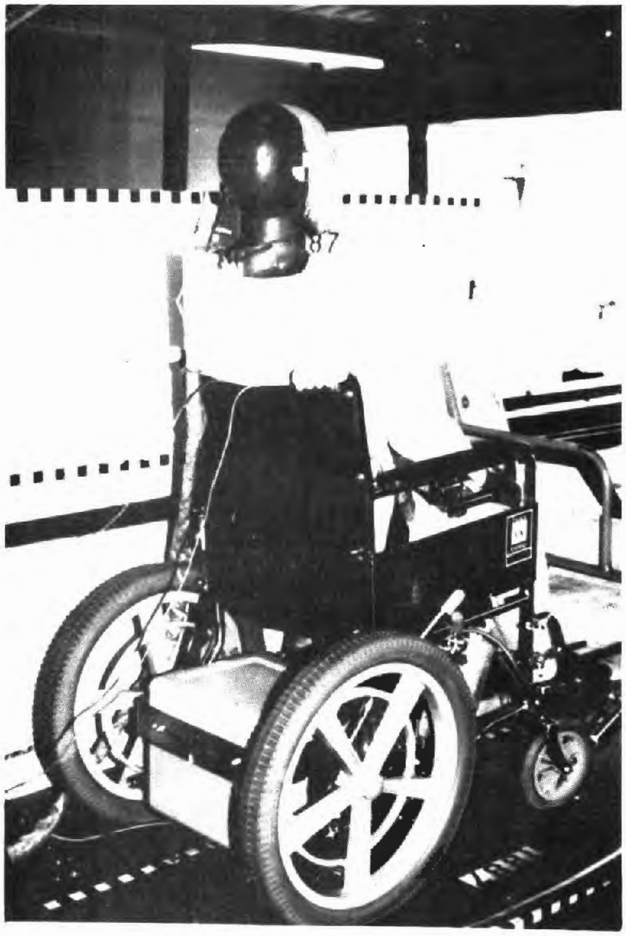
TEST ACTION:

There was significant decoupling observed: The dummy slid forward from the wheelchair, jackknifed about the waist and hit its forehead severely on the steel seat armrest. The right and left forearms also struck the armrest. The dummy's head strike is evident by the mark on the forehead in Figure A-45.

TEST RESULTS:

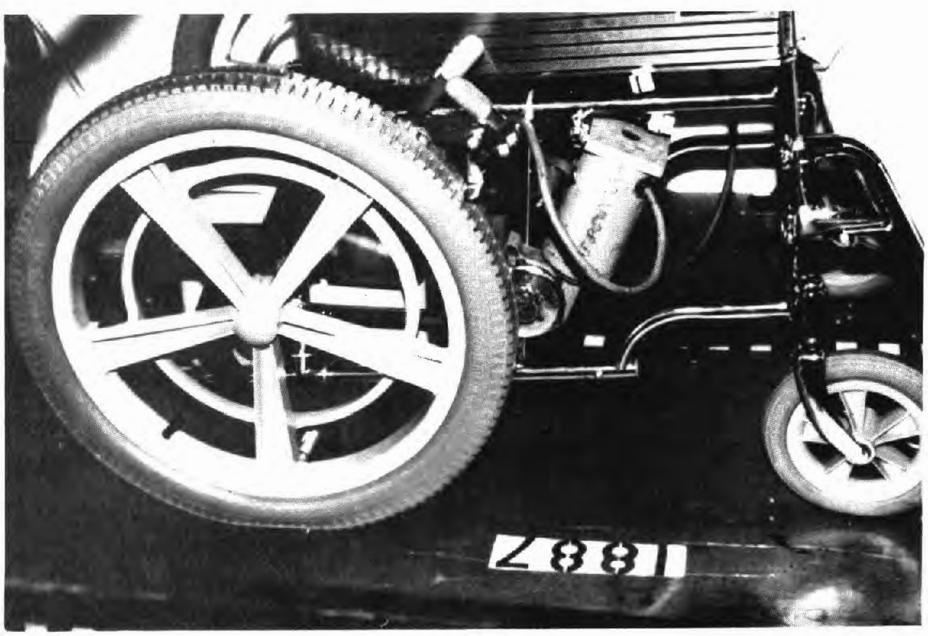
WHEELCHAIR: The wheelchair received major damage. Moderate damage occurred to the left and right hub struts at the intersections with the lower support members. The lower support members bent at the cross strut joints. The castor support radii increased and the forward frame yielded at the castor mounts. Both armrest assemblies bent at their mounting points.

DUMMY: The head accelerometer wires were damaged during deceleration so no HIC level could be determined. The CSI was 58 and the peak seat belt load was 350 pounds. One of the restraint bolts was instrumented with a strain gauge to measure load and measured a peak load of 4000 pounds. Head excursion was 42 inches.



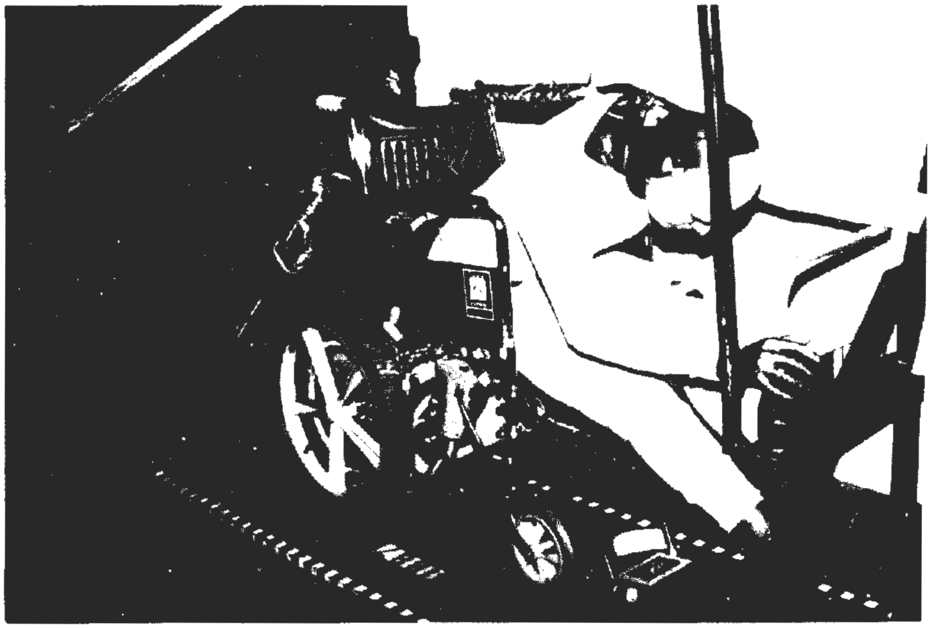
Test 1887 Test Configuration

Figure A-42



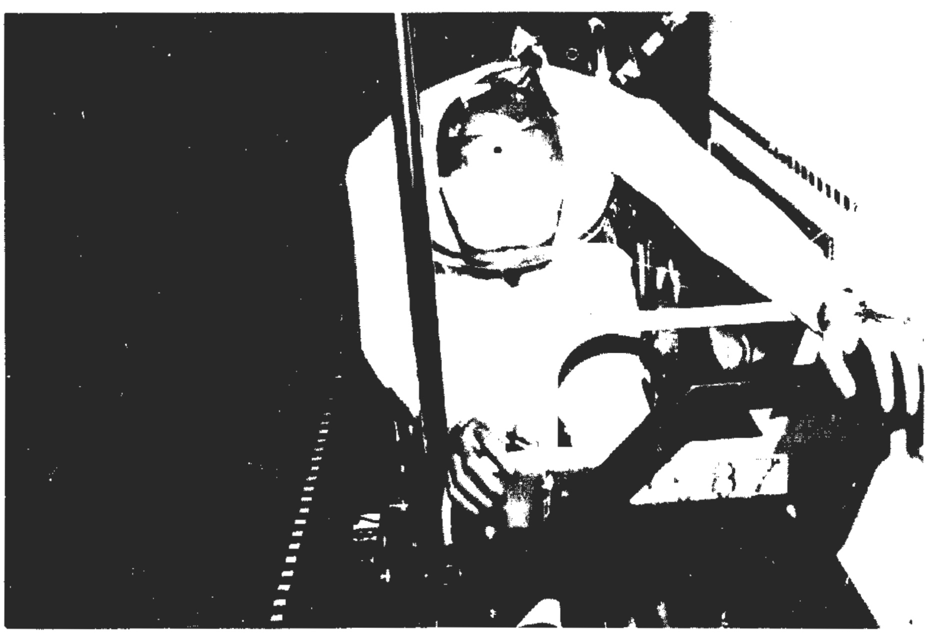
Test 1887 Test Configuration Showing Frame Anchor

Figure A-43



Test 1887 Damage

Figure A-44



Test 1887 Damage - Showing Dummy Head Strike

Figure A-45

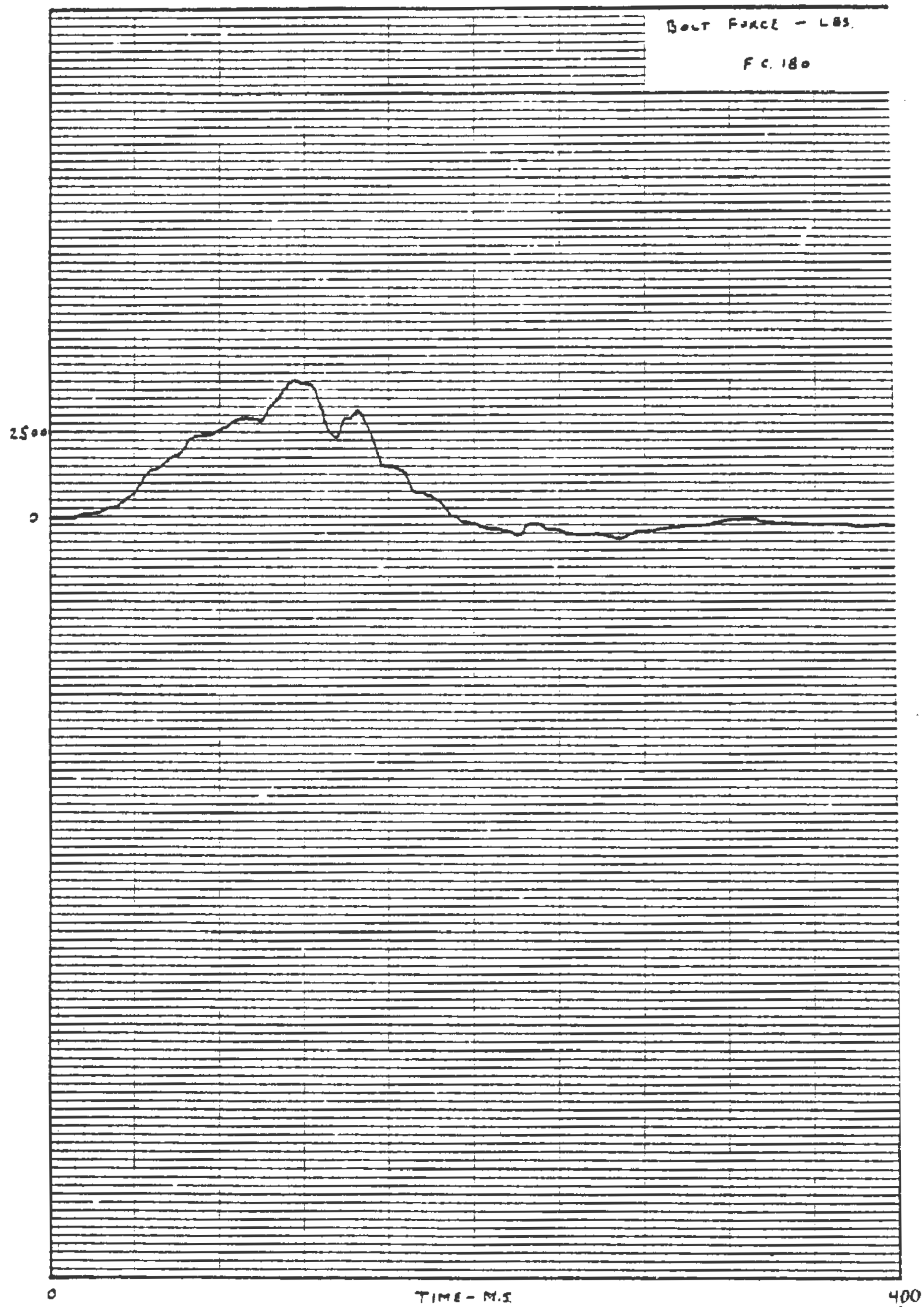


Figure A-46 Frame Anchor Belt Force Data Trace

Test 1887

TEST NUMBER: 1970 | SLED SPEED: 20.8 mph

FACING DIRECTION: Forward | CRASH PULSE: 9.5 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Belt around armrest

DUMMY: Lap belt to axles

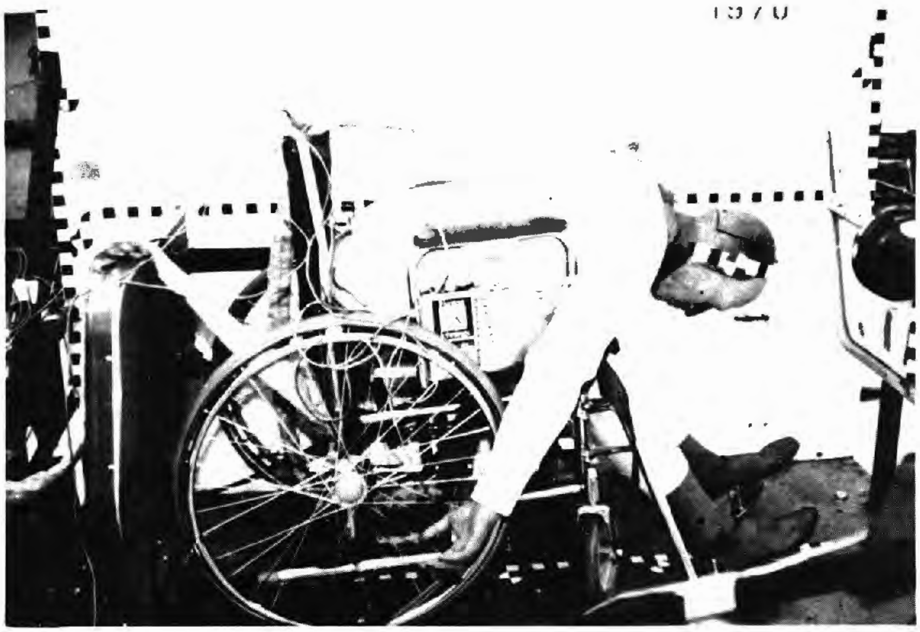
TEST ACTION:

The dummy was pitched forward from the wheelchair, and its arms hit the steel armrest. The body continued its jackknife motion with the head just missing the steel armrest. The legs straightened at the knees, the dummy's posterior lifted into the air, and the dummy's forehead struck his left shin. The excursions are listed in Table A-4.

TEST RESULTS:

WHEELCHAIR: Damage to the wheelchair was moderate. The frame was bent during the dynamic event. The securement belt pressed the armrests toward each other.

DUMMY: The HIC was 670 and the CSI was 149. The seat belt load peaked at 260 pounds and the securement belts peaked at 1500 pounds. Head excursion was 32 inches.



Test 1970 Final Position

Figure A-47

TABLE A-4 EXCURSION, TEST 1970

Belt Around Armrest
Forward Facing Manual Wheelchair (S/N 1784653)
20 mph, 10 Gs
14 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	11.75	11.75	11.75
Rear axle to rear of sled	24	24	24
Front axle to floor	3.75	3.75	3.75
Front axle to rear of sled	43.5	43	42
Knee point to floor	21	17.5	17
Knee point to rear of sled	42.5	42.5	43.5
Head point to overhead camera*	15		
Head point to floor**	48	24.5	
Head point to on-board side camera*	51		
Head point to rear of sled**	36	53	
Ankle point to floor	6.5	4	4.5
Ankle point to rear of sled	49	51.5	53.5
Wheelchair front axle to edge of sled	11.5	13	
Wheelchair rear axle to edge of sled	10.5	12	
Shoulder to floor	39.5	27	26.5
Shoulder to rear of sled	23.5	45.5	46

*Measured to head bolt.

**Measured to target.

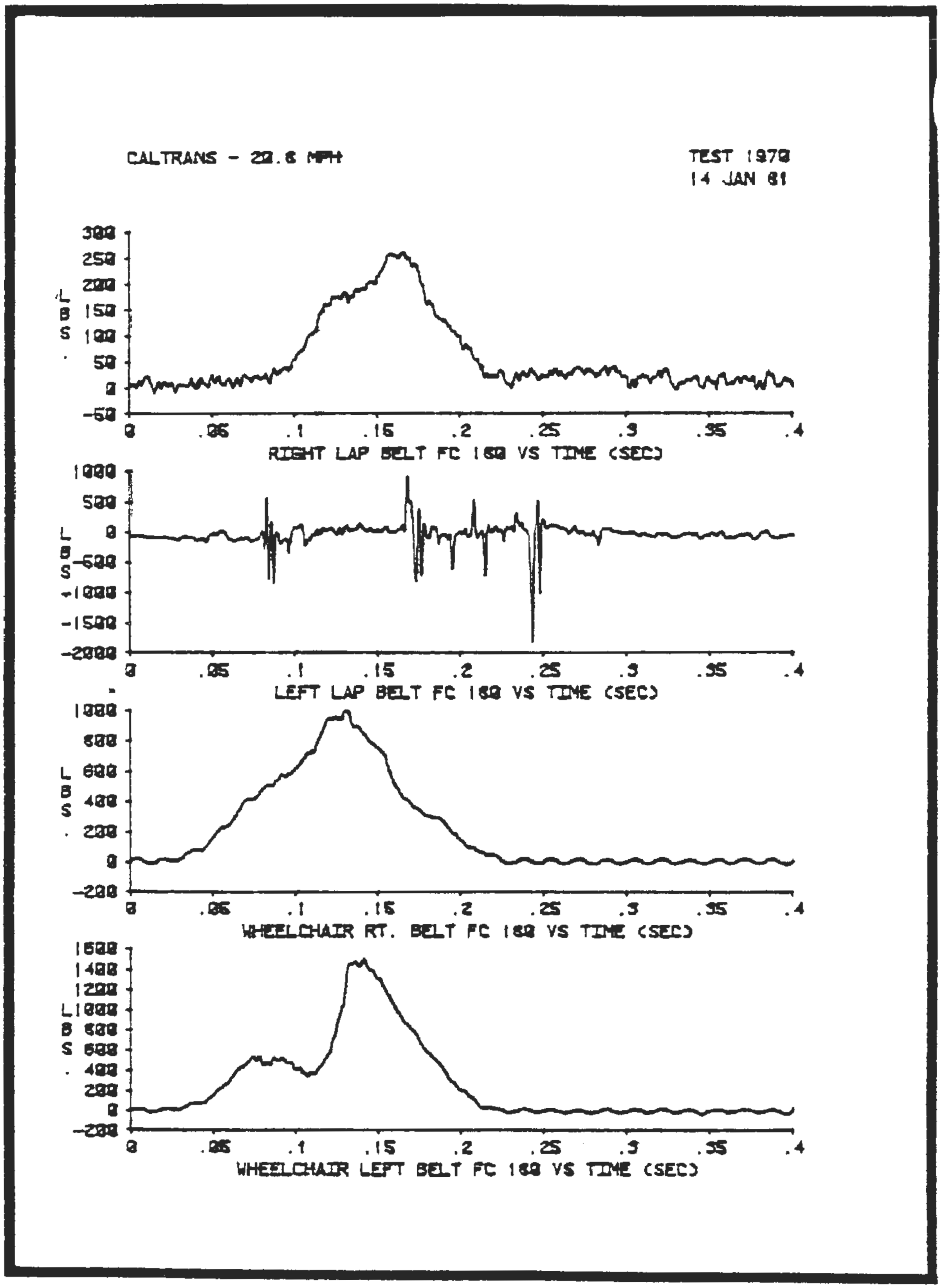


FIGURE A-48 BELT FORCES, TEST 1970

TEST NUMBER: 1971

FACING DIRECTION: Forward

SLED SPEED: 20.5 mph

CRASH PULSE: 10.0 g's

CHAIR TYPE: Electric

SECUREMENT

WHEELCHAIR: Belt around armrest

DUMMY: Lap belt to axles

TEST ACTION:

The dummy jackknifed about his waist and struck his head and left elbow on the armrest of the bus seat. The wheelchair's frame was crushed from the belts pushing in at the armrest.

TEST RESULTS:

WHEELCHAIR: The wheelchair received major damage. The frame was bent from the crushing action of the belt. The castors splayed apart from the downward force of the belt. Excursions are listed in Table A-5.

DUMMY: The HIC was 1437 (beyond the level of acceptability) and the CSI was 141. The head excursion was 39 inches. The lap belt peaked at 140 pounds while the securement load reached 1820 pounds.

TABLE A-5 **EXCURSION, TEST 1971**

Belt Around Armrest
Forward Facing Electric Wheelchair (S/N 1794644)
20 mph, 10 Gs
14 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	10	10	10
Rear axle to rear of sled	22	21.5	21.5
Front axle to floor	3.75	3.5	3.5
Front axle to rear of sled	45.5	45	45
Knee point to floor	22	17	15.5
Knee point to rear of sled	43.5	43	44
Head point to overhead camera*.	14		
Head point to floor**	49.5	35.5	
Head point to on-board side camera*	49		
Head point to rear of sled**	27	52	
Ankle point to floor	8	4.5	3.5
Ankle point to rear of sled	49.5	53	52
Wheelchair front axle to edge of sled	12	11	
Wheelchair rear axle to edge of sled	11	12	
Shoulder to floor	40.5	35	34.5
Shoulder to rear of sled	25	43.5	42.5

*Measured to head bolt.

**Measured to target.

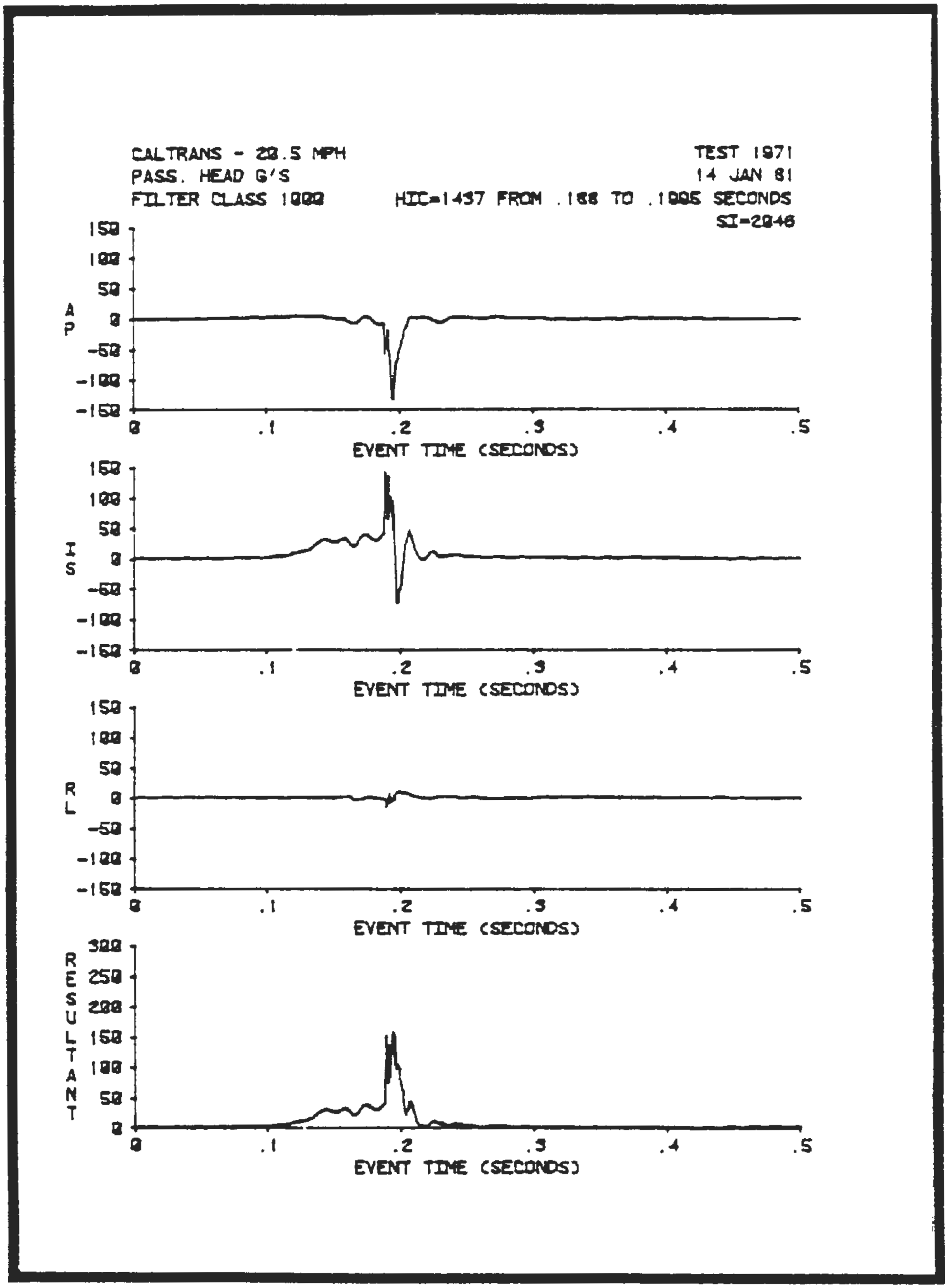


FIGURE A-49 HEAD ACCELERATION, TEST 1971

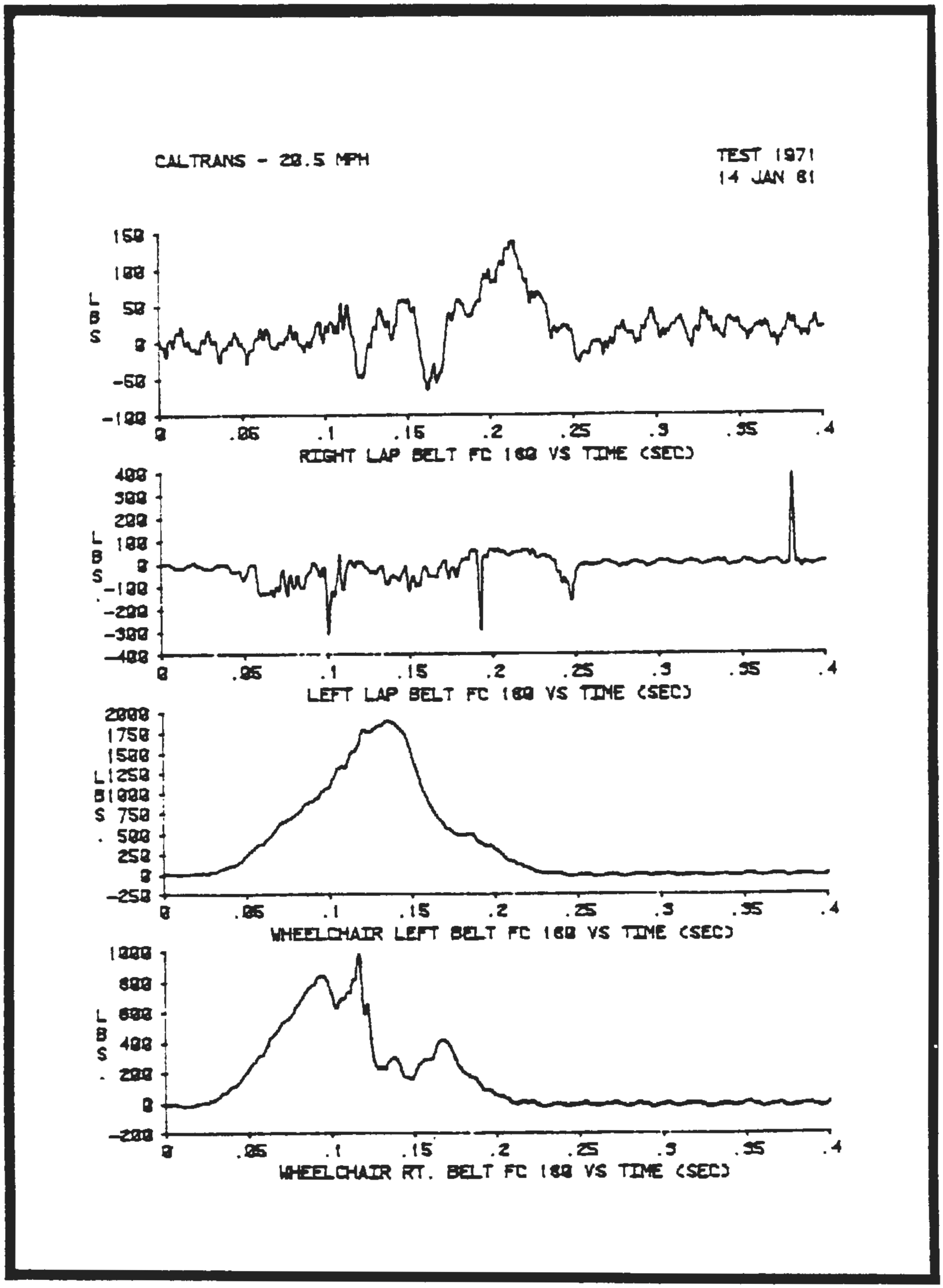


FIGURE A-50 BELT FORCES, TEST 1971

TEST NUMBER: 1976 | SLED SPEED: 21.2 mph

FACING DIRECTION: Forward | CRASH PULSE: 11.0 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Simulated automatic rim pin

DUMMY: Lap belt to axles

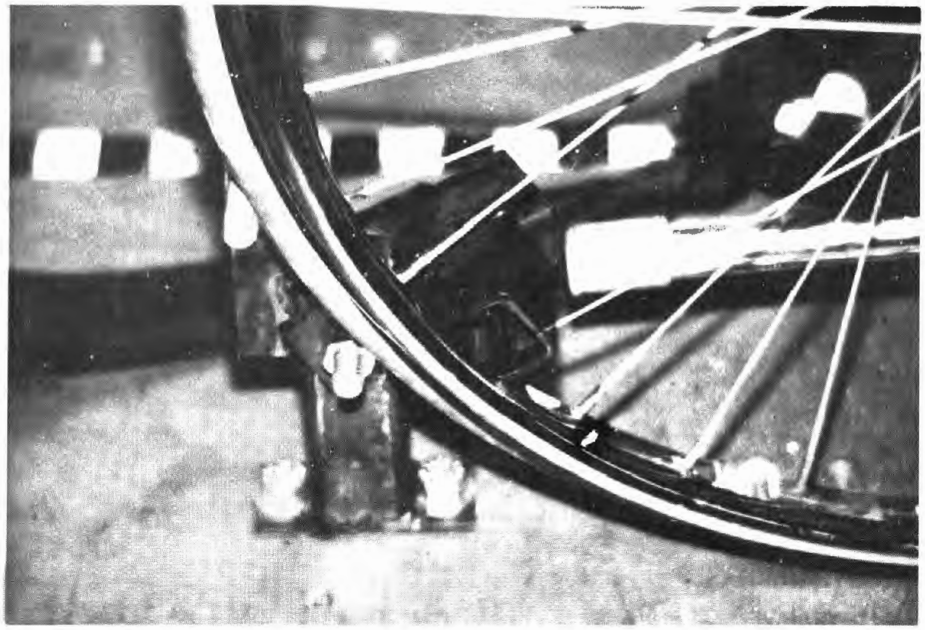
TEST ACTION:

The upper torso of the dummy rotated about the waist. The dummy's head struck his left shin while both legs kicked forward.

TEST RESULTS:

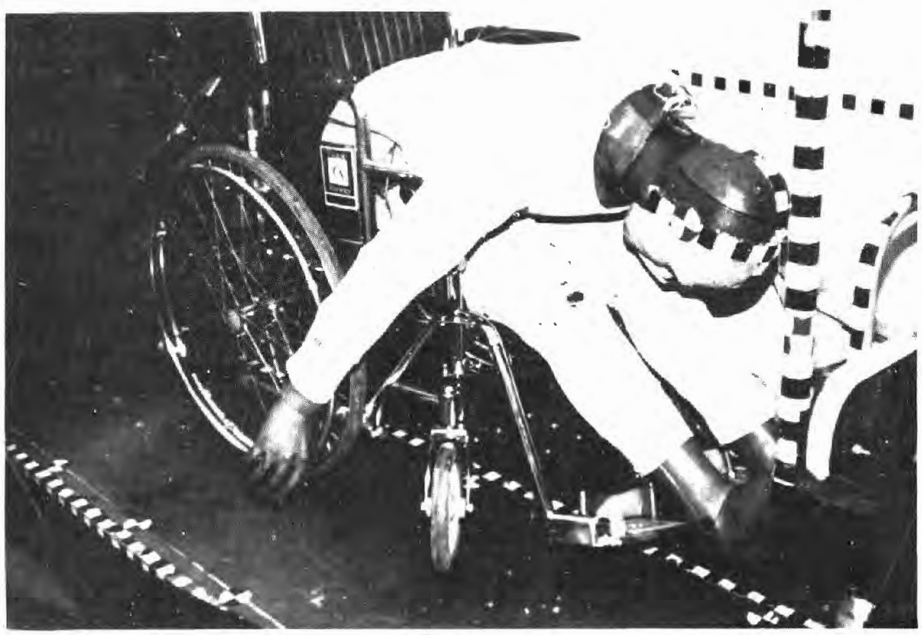
WHEELCHAIR: The wheelchair damage, limited to the rear wheels, was considered to be moderate. Figure A-51 is a closeup of the wheelchair and securement contact.

DUMMY: The HIC was 1029 (very serious or fatal injury). The CSI was 140 and the peak belt load was 775 pounds. Head excursion was 27 inches.



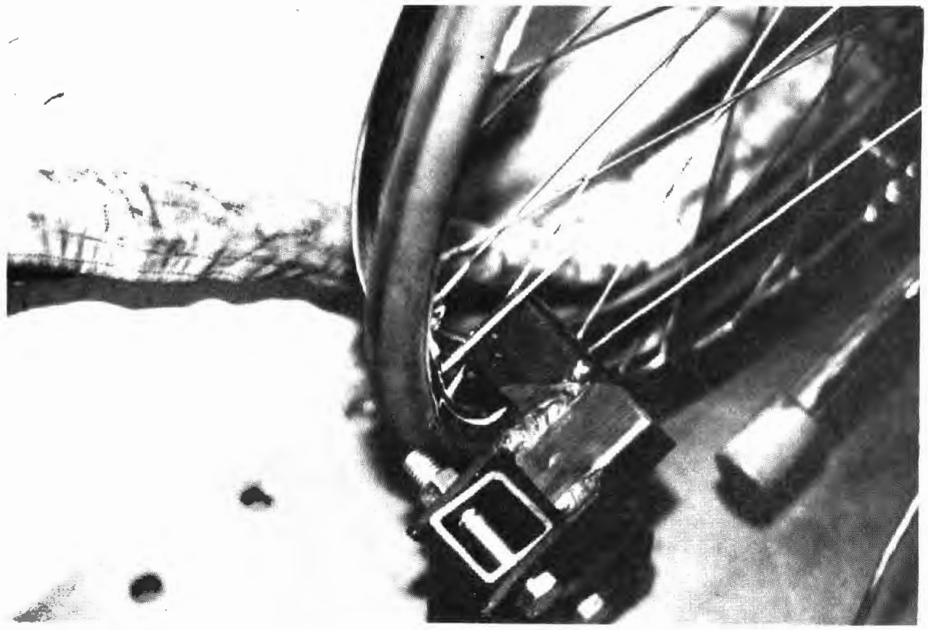
Test 1976 Right Wheel Securement

Figure A-51



Test 1976 Post-Test Condition

Figure A-52



Test 1976 Post-Test Left Wheel Securement

Figure A-53

TABLE A-6 EXCURSION, TEST 1976

Simulated Automatic Rim Pin Securement
Forward Facing Manual Wheelchair (S/N 1784684)
20 mph, 10 Gs
22 January 1981

Type of Measurement	Distance (inches)		
	Before Test	After Test	
		Right	Left
Rear axle to floor	11.75	11.75	12
Rear axle to rear of sled	24	24	24
Front axle to floor	3.75	3.75	3.75
Front axle to rear of sled	43.5	42	42.5
Knee point to floor	22	15	16
Knee point to rear of sled	42.5	44.5	45
Head point to overhead camera*	16.5		
Head point to floor**	48.5	22.5	
Head point to on-board side camera*	51.5		
Head point to rear of sled**	23.5	55	
Ankle point to floor	7	4.5	4
Ankle point to rear of sled	48.5	56.5	56.5
Wheelchair front axle to edge of sled	12.5	12	
Wheelchair rear axle to edge of sled	10.5	11	
Shoulder to floor	40	26.5	25.5
Shoulder to rear of sled	22.5	47	48

*Measured to head bolt.

**Measured to target.

TEST NUMBER: 1979

FACING DIRECTION: Side

SLED SPEED: 20.7 mph

CRASH PULSE: 9.6 g's

CHAIR TYPE: Manual

SECUREMENT

WHEELCHAIR: Padded side panel in trajectory path

DUMMY: Lap belt to axles

TEST ACTION:

First the wheelchair, then the dummy's shoulder and head struck the padded side panel. As the dummy and wheelchair contacted the padded wall, they rebounded from the panel, rotated about the left caster, and fell off the test sled. The final position of the dummy and wheelchair is shown in Figure A-55. The excursions are listed in Table A-7.

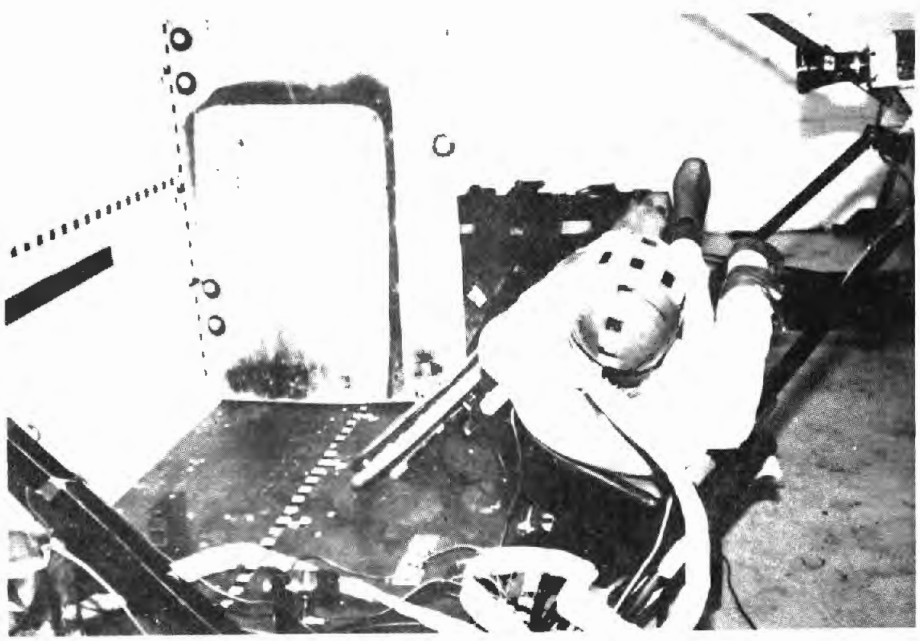
TEST RESULTS:

WHEELCHAIR: Damage to the wheelchair was negligible (minor).

DUMMY: The HIC was 351 and the CSI was 175. The lap belt loads peaked at 280 pounds. Head excursion was not measured.

Test 1979 Seating Position

Figure A-54



Test 1979 Final Position

Figure A-55

TABLE A-7 **EXCURSION, TEST 1979**

Padded Side Panel
Side Facing Manual Wheelchair (S/N 1812233)
20 mph, 10 Gs
23 January 1981

<table>
<tr><th rowspan="3">Type of Measurement</th><th colspan="4">Distance (inches)</th></tr>
<tr><th colspan="2">Before Test</th><th colspan="2">After Test</th></tr>
<tr><th>Right</th><th>Left</th><th>Right</th><th>Left</th></tr>
<tr><td>Rear axle to floor</td><td colspan="2">11.75</td><td>8</td><td>9.5</td></tr>
<tr><td>Rear axle to rear of sled</td><td colspan="2">34</td><td></td><td>61.5</td></tr>
<tr><td>Front axle to floor</td><td colspan="2">3.75</td><td>-5</td><td>9</td></tr>
<tr><td>Front axle to rear of sled</td><td>36</td><td>56.5</td><td></td><td>45</td></tr>
<tr><td>Knee point to floor</td><td colspan="2">23</td><td>15</td><td>18</td></tr>
<tr><td>Knee point to rear of sled</td><td>41.5</td><td>52</td><td>48</td><td>49</td></tr>
<tr><td>Head point to overhead camera*</td><td colspan="2">13</td><td colspan="2"></td></tr>
<tr><td>Head point to floor**</td><td colspan="2">49</td><td colspan="2">26</td></tr>
<tr><td>Head point to on-board side camera*</td><td colspan="2">52</td><td colspan="2"></td></tr>
<tr><td>Head point to rear of sled**</td><td colspan="2">45.5</td><td colspan="2">16.5</td></tr>
<tr><td>Ankle point to floor</td><td colspan="2">8</td><td>16.5</td><td>14</td></tr>
<tr><td>Ankle point to rear of sled</td><td>41</td><td>52</td><td>63.5</td><td>64.5</td></tr>
<tr><td>Wheelchair front axle to wall</td><td colspan="2">5.5</td><td colspan="2">1.5</td></tr>
<tr><td>Wheelchair rear axle to wall</td><td colspan="2">4</td><td colspan="2">18</td></tr>
<tr><td>Shoulder to floor</td><td colspan="2">39</td><td>20</td><td>16.5</td></tr>
<tr><td>Shoulder to rear of sled</td><td>37.5</td><td>54</td><td>19.5</td><td>21</td></tr>
</table>

*Measured to head bolt.

**Measured to target.

APPENDIX B

Analytical Stress Analysis On Everest and Jennings Model P8AU 250-770 Wheelchair Using Forward "T-Bar" Restraint

Crashworthiness of Wheelchair Securement Systems
Caltrans Contract No. 64084-C

May 1979

Submitted to:

Department of Transportation
Division of Mass Transportation
1120 N Street
Sacramento, California 95814

Submitted by:

Minicars, Inc.
55 Depot Road
Goleta, California 93017

FOREWARD

This report presents an analytical evaluation of the effect of the T-bar wheelchair restraint system and a comparison of that analysis with test data. This effort was performed in partial fulfillment of the Wheelchair Testing Program conducted by Minicars, Inc. under Caltrans Contract No. 64084-C.

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Urban Mass Transportation Administration or the State of California. The report does not constitute a standard, specification or regulation.

1.0 INTRODUCTION

Over the past several years both government agencies and private industry have studied the problem of providing adequate transportation for handicapped people. One of the particular concerns has been the development of vehicles accessible to wheelchair patients, i.e., vehicles that will accept and properly secure wheelchair occupants without disturbing them. A vehicle with this feature would eliminate the struggle a disabled person currently undergoes to move from a wheelchair to an automobile seat. In collisions, such vehicles would present a new set of problems, even in minor accidents, regarding the protection of handicapped occupants. As part of the effort to investigate these problems, Caltrans awarded Minicars, Inc. of Goleta, California a contract (No. 64048-C) to study "Crashworthiness of Wheelchair Securement Systems." The major effort under this contract was to dynamically test a variety of wheelchair securement systems under crash environment in order to aid in the selection and design of the most appropriate securement method. However, since full scale dynamic testing is a relatively expensive method of evaluating design, a secondary goal of the contract was to determine the feasibility of analytically evaluating wheelchair securement systems. This report presents the method and results of the analytical study.

The analytical study was conducted on the forward T-bar securement system in the forward facing position. Figure 1 illustrates the T-bar securement system concept. The goal of the effort was to establish the methodology for the analysis and to verify its accuracy by comparison between structural analysis, static test data and dynamic test data. The specific tasks to be accomplished were as follows:

1. Inspect the wheelchair structure, securement system, and available test data to identify the system response, collapse mode, location of initial failure, and structural elements critical in transmitting the restraint loads.

2. Perform a detailed static stress analysis to determine the stress distributions in the critical elements.

3. Identify the load range as deceleration levels corresponding to elastic behavior of the system.

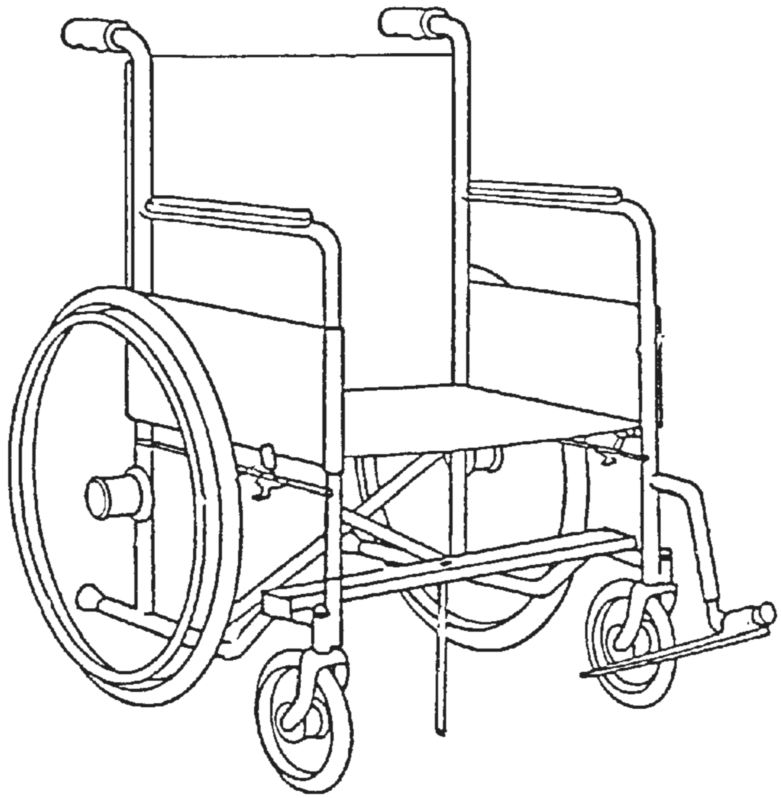


Figure 1. Everest and Jennings Wheelchair with
a Forward Placed T-bar Restraint

4. Identify the load range corresponding to elastic-plastic behavior of the system. The upper limit of this range represents the collapse load of the structure.

5. Determine the failure mechanism and define the deceleration limit for the securement system.

This report documents the fulfillment of the above tasks. It is presented in five sections including this introduction. Section 2.0 describes the analytical model used for the analysis. Section 3.0 presents the analytical evaluations of the elastic range and elastic plastic ranges of the system. Section 4.0 correlates the analytical data with static and dynamic test data. Section 5.0 presents the conclusions and recommendations resulting from this study.

2.0 STRUCTURAL ANALYSIS OF WHEELCHAIR AND SECUREMENT SYSTEM

2.1 Method of Analysis

The analysis was conducted for an Everest and Jennings Model P8AU 250-770 wheelchair with forward placed T-bar securement system. Figure 2 presents a photograph of a wheelchair prior to test. The analysis utilized a finite element model with beam-type elements. The models were run on the G.E. Timeshare System program "STRuctural Engineering System Solver" (STRESS). Complete description of STRESS can be found in the Mark III Foreground Service Users Guide 5202.01 issued by General Electric. The STRESS program is based on the consistant deformation principle and solves the stiffness matrix for internal loads at the joints. The output is in the form of moments, shears, and axial loads, which must be converted to stresses by hand calculations. The basic assumptions of the program are elementary beam theory, elastic behavior, and static loadings.

The method of analysis is summarized as follows:

1. Select node points which describe the wheelchair geometry.

2. Identify the structural elements and boundary conditions.

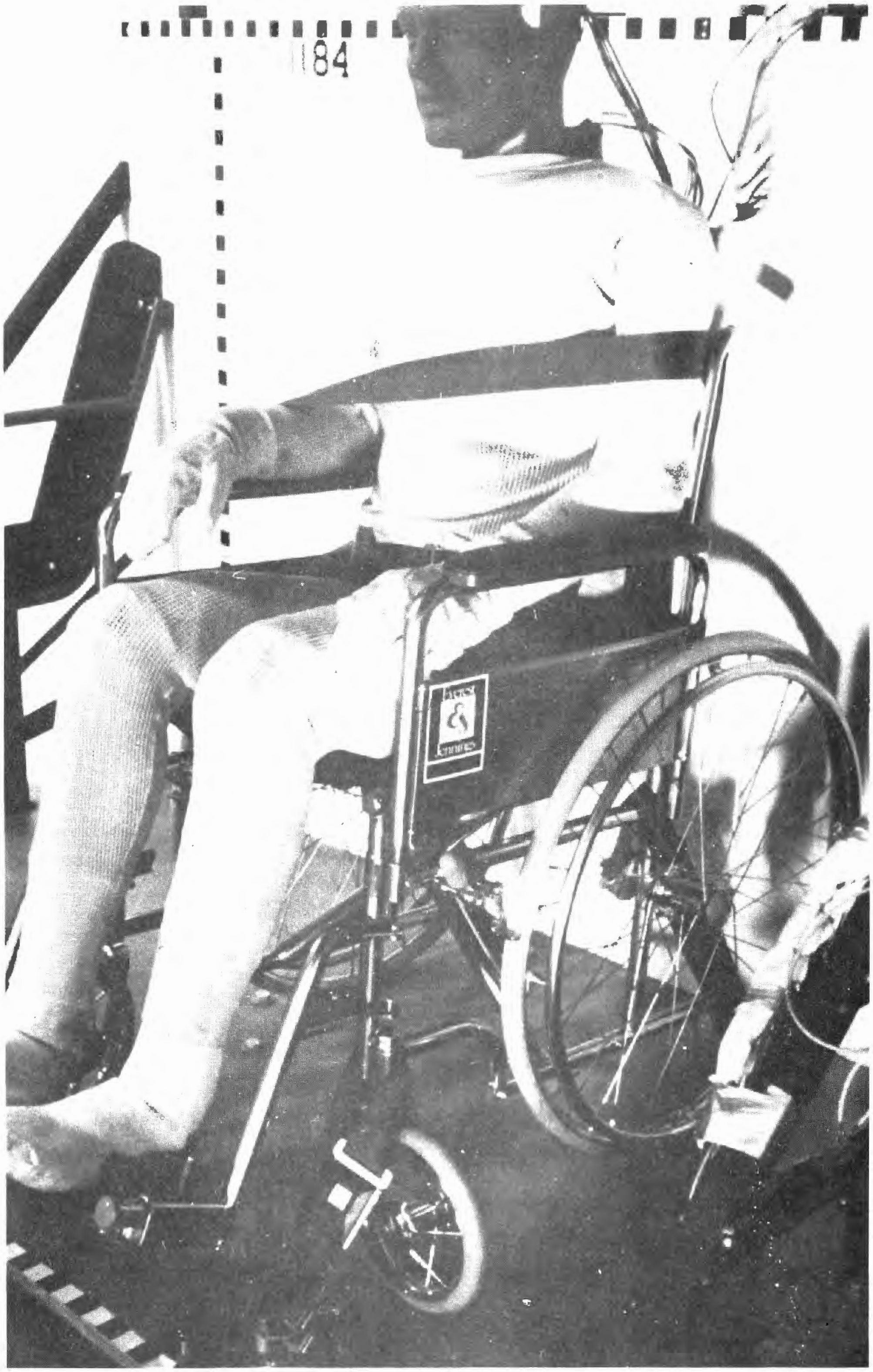


Figure 2. Detail View of the Structure of an Everest and Jennings Wheelchair

3. Calculate section properties of each type of member.

4. Determine applied loads for each loading condition, based on a unit load.

5. Run computer program "STRESS" with output in the form of internal loads.

6. Calculate critical stresses based on the computer output loads.

7. Calculate elastic limit loading by proportioning the critical stresses to the yield strength of the material.

8. Calculate elastic-plastic limit by limit load analysis techniques, i.e., assumption of elastic-perfectly plastic material behavior.

The accuracy of the predictions based upon this model are dependent upon the appropriateness of the basic assumptions to the system under analysis. The first assumption, beam theory, is suitable for the wheelchair analysis since most of the structure is composed of long slender members that can be represented by their centroidal axis. The only areas of where this assumption is inappropriate are the large connectors used for removable parts, such as the foot rests, castors, etc. The assumptions of elastic behavior and static loading are necessary to reduce the complexity of the analysis and render it economically feasible. To remove these assumptions and perform a true dynamic, nonlinear study would increase the cost of the analysis five to ten times.

2.2 Description of the Finite Element Model

As discussed previously, the structural system was modeled as a space frame structure composed of slender, beam-type elements. The complete geometry of the wheelchair was modeled with the exception of the seat, back, and side panels. The resulting model contained 61 elements connecting 52 node points. Figure 3 shows the analytical model. The nodes are identified by the plain numbers and the elements by the circled numbers.

The wheelchair structure itself contained several members which were released in certain degrees of freedom. To properly simulate

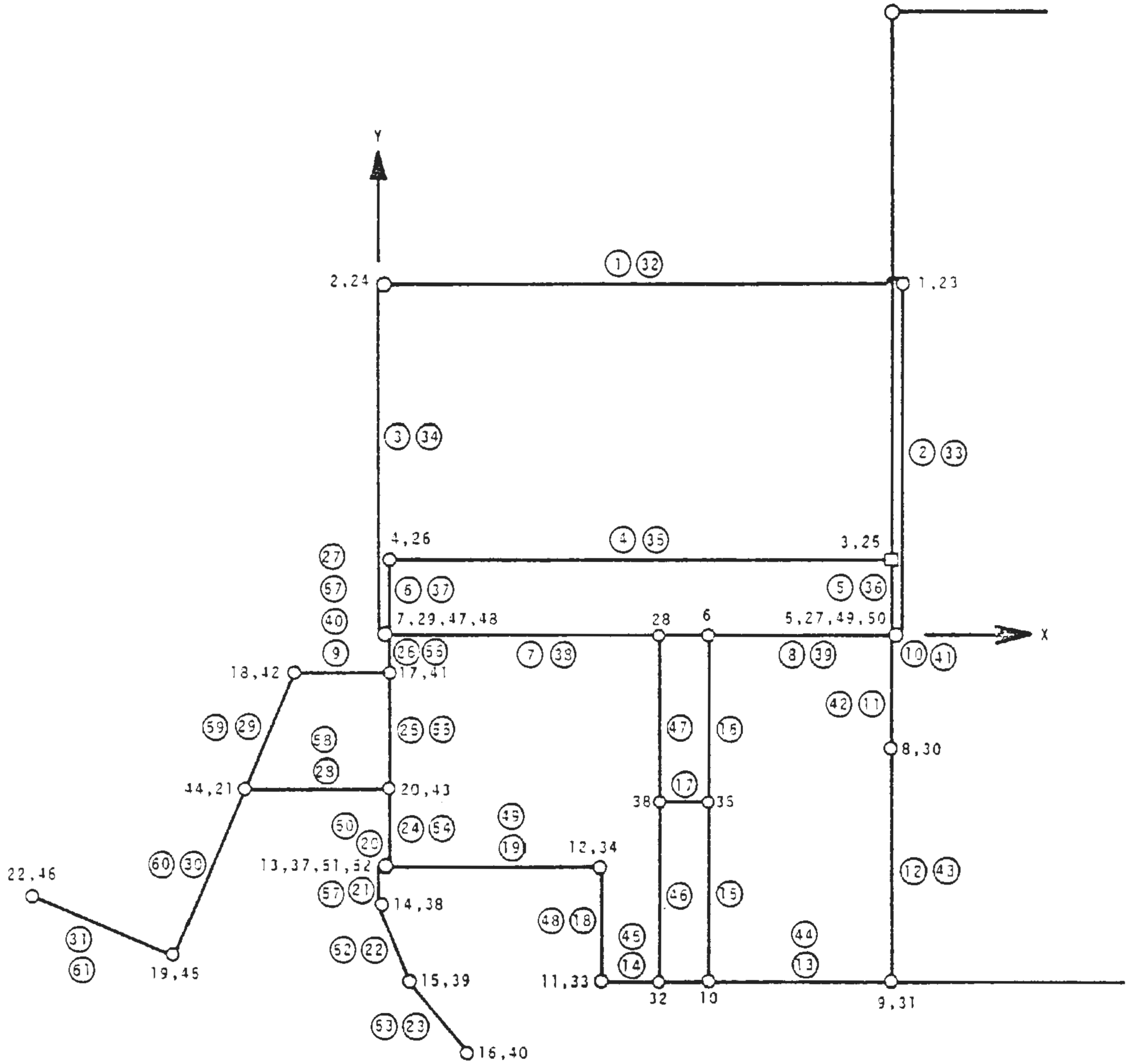


Figure 3. Finite Element Model of Wheelchair

Note:

1. Plain numbers represent node points
2. Circled numbers represent elements

The possible movements of these members it was necessary to release the following locations:

1. The seat supports are free to rise vertically as the wheelchair collapses. Thus, the vertical movement of elements 5, 6, 36 and 37 were released at joints 5, 7, 27 and 29.

2. The diagonal braces from the seat to the frame are free to rotate. Therefore, the end rotations of members 15, 16, 46 and 47 were released at joints 6, 10, 28 and 32.

3. The bolt connecting the diagonal braces is free to rotate requiring the rotational release of member 17 at joint 35.

4. The front castors are free to rotate about their vertical axis. This is represented by releasing the rotational restraint of members 21 and 57 at joints 13 and 51.

5. The foot rest attachment is a slip-lock arrangement with an indeterminate degree of restraint. These joints (17, 20, 41 and 43) were simulated as fixed. The assumption of fixity is acceptible provided the joint is stronger than the connecting members, forcing any failures to occur in the basic elements and not in the joints. A separate analysis of the joint degree of fixity is required to remove this assumption.

The section properties of the various elements were calculated and are presented in Table 1. The properties required by the STRESS program are the area of the cross section, the effective area resisting shear in the y and z directions, the torsional stiffness constant, and the moments of inertia of the cross section about the y and z axis. The element coordinate system places the x axis along the member with the y and z axes, the centroidal axes at the cross section. The major portion of the elements were 18 gage, 7/8 tubular steel sections. The rigid connection of the castors to the frame and the arm rests to the frame are modeled as solid rectangular members. The 1/4-inch bolt connecting the cross diagonals was modeled as a solid circular section.

The boundary conditions for the model were based upon observation of the test photographs. During both the static and dynamic

Table 1. Section Properties of Elements

Element No.	Area (in.^{2})	Torsional Constant (in.^{4})	Moment of Inertia y axis (in.^{4})	Moment of Inertia x axis (in.^{4})
1 through 8 11 through 16 18, 19 24 through 29 42 through 49 54 through 61 21, 51	.1272	.0218	.0109	.0109
9, 10, 40, 41, 20, 50	.75	.0493	.0156	.0156
22, 23, 52, 53	.125	.00059	.00016	.0104
17	.307	.00038	.00019	.00019

tests in the forward facing position the T-bar slid backward as the chair tipped forward, rotating about the forward castor centers. The final resting position was with the footrest against the platform and the T-bar against the lower frame of the chair as shown in Figure 4. The support nodes used in the model were nodes 19 and 45, the rear of the foot rests, joints 16 and 40, the axis of the front castors and joints 11 and 33, the location of the T-bar securement system. The rotational degrees of freedom were released at all of these supports.

The loading condition for the forward facing mode was simulated by loads applied at point of attachment of the seat belt. The seat belt is assumed to act at an angle of 30 degrees to the plane of the seat. A unit seat belt load of 1000 pounds was applied, 500 lbs on each side. The concept of a unit load was utilized to facilitate the calculation of the elastic limit load by simple proportioning. The weight of the dummy against the seat was neglected.

2.3 Calculation of Stresses in the Linear Range

The model described in Section 2.2 was used as input to STRESS. The output from the program consists of axial load, transverse shears, torque and bending moments at the ends of each member. The reactions at the supports and the free joint displacement are also available as output. Table 2 presents the STRESS output for the forward facing loading condition.

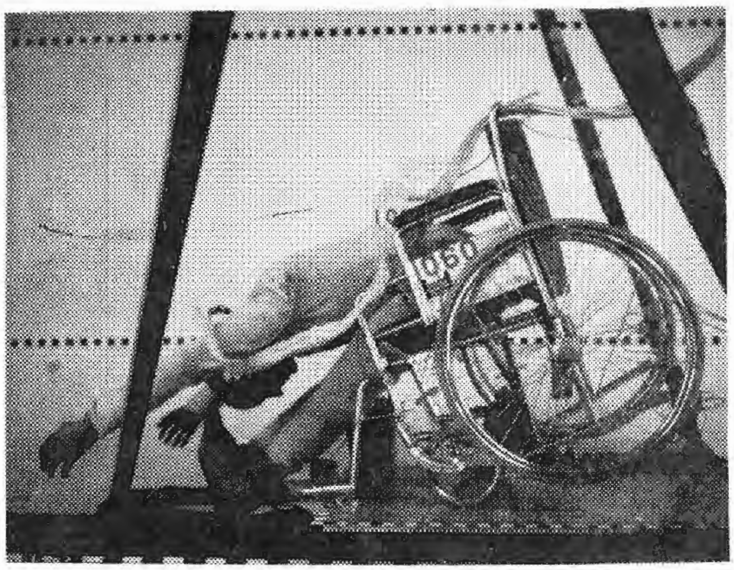
The actual stresses in the member are obtained by applications of the standard beam formulas. The direct stress is

$$\sigma_d = \frac{P}{A} \pm \frac{M_y Z}{I_y} \pm \frac{M_z Y}{I_z}$$

For the case of tubular members this is reduced to

$$\sigma_d = \frac{P}{A} \pm \frac{\sqrt{(M_y^2 + M_z^2)}\ r}{I}$$

where r = radius and $I = I_y = I_z$. The location of the maximum stress is the extreme fiber tested at an angle



b) Post Test Position

Figure 4. Dynamic Test of T-bar Securement System

Table 2. Internal Loads for Front Facing Wheelchair with T-bar Securement System Generated by 1000 lb Seat Belt Load

MEMBER FORCES

MEM	JT	AXIAL	SHEAR-Y	SHEAR-Z	TORSION	MOMENT-Y	MOMENT-Z
1	1	-1.81	2.01	-3.67	-0.91	25.82	10.95
1	2	1.81	-2.01	3.67	0.91	36.49	23.25
2	1	2.01	-1.81	-3.67	25.82	-0.91	10.95
2	27	-2.01	1.81	3.67	-25.82	74.21	-47.15
3	2	-2.01	1.81	3.67	36.49	0.91	23.25
3	29	2.01	-1.81	-3.67	-36.49	-74.21	12.95
4	3	-14.06	0.00	-9.64	-56.49	65.83	15.75
4	4	14.06	-0.00	9.64	56.49	98.04	-15.75
5	3	0.	-14.06	-9.64	65.83	-56.49	15.75
5	5	0.	14.06	9.64	-65.83	80.59	-50.89
6	4	0.	14.06	9.64	98.04	56.49	-15.75
6	7	0.	-14.06	-9.64	-98.04	-80.59	50.89
7	6	589.28	3.88	-21.25	-72.62	60.35	16.35
7	7	-589.28	-3.88	21.25	72.62	173.44	26.31
8	5	544.10	70.36	36.10	-72.62	-67.03	292.60
8	6	-544.10	-70.36	-36.10	72.62	-149.57	129.57
9	7	3.67	-2.01	-1.81	-12.95	39.20	-77.23
9	29	-3.67	2.01	1.81	12.95	-36.49	74.21
10	5	-3.65	2.02	1.81	47.15	23.11	77.23
10	27	3.65	-2.02	-1.81	-47.15	-25.82	-74.20
11	5	-177.62	95.23	22.81	21.90	-230.43	390.64
11	8	177.62	-95.23	-22.81	-21.90	139.21	-9.71
12	8	-177.63	95.23	22.81	21.90	-139.21	9.71
12	9	177.63	-95.23	-22.81	-21.90	-31.84	704.54
13	9	-95.23	177.63	-22.81	-31.84	-21.90	704.54
13	10	95.23	-177.63	22.81	31.84	153.74	361.21
14	10	-137.26	242.79	-73.51	-31.84	47.94	-8.01
14	11	137.26	-242.79	73.51	31.84	209.33	857.77
15	35	-79.00	24.00	42.03	169.36	-64.73	249.67
15	10	79.00	-24.00	-42.03	-169.36	-372.53	0.
16	6	-84.27	24.66	-45.18	74.05	154.18	0.00
16	35	84.27	-24.66	45.18	-74.05	303.19	249.68
17	35	-3.15	1.32	108.05	0.	-144.23	1.50
17	36	3.15	-1.32	-108.05	0.	-71.88	1.14
18	11	-186.61	57.89	-78.44	-209.33	-31.84	857.77

Table 2 (Cont'd)

0043	18	12	186.61	-57.89	78.44	209.33	345.59	-626.21
0044	19	12	57.89	-186.61	78.44	-345.59	-209.33	-626.21
0045	19	13	-57.89	186.61	-78.44	345.59	-378.95	-773.37
0046	20	13	0.00	469.04	-264.92	284.45	397.38	703.57
0047	20	37	-0.00	-469.04	264.92	-284.45	0.00	0.00
0048	21	37	-469.04	-264.92	0.00	0.	-0.00	-284.45
0049	21	14	469.04	264.92	-0.00	0.	-0.00	-112.93
0050	22	14	-533.88	-71.77	-0.00	0.	0.00	112.93
0051	22	15	533.88	71.77	0.00	0.	0.00	-306.19
0052	23	15	-518.99	144.34	0.00	0.	-0.00	306.19
0053	23	16	518.99	-144.34	-0.00	0.	-0.00	-0.00
0054	24	20	-655.65	-207.03	78.44	-18.43	161.38	-28.64
0055	24	13	655.65	207.03	-78.44	18.43	-357.98	-488.93
0056	25	17	-490.46	-119.80	41.48	148.69	114.08	-104.95
0057	25	20	490.46	119.80	-41.48	-148.69	-259.27	-314.34
0058	26	7	-5.89	-573.41	34.56	310.68	230.44	-37.53
0059	26	17	5.89	573.41	-34.56	-310.68	-282.27	-822.58
0060	27	17	453.61	-434.57	6.93	-168.19	-161.99	-927.53
0061	27	18	-453.61	434.57	-6.93	168.19	141.21	-526.18
0062	28	20	-87.23	-165.19	36.96	-97.39	-167.11	-342.98
0063	28	21	87.23	165.19	-36.96	97.39	0.32	-400.39
0064	29	18	624.08	226.05	6.93	63.54	-210.22	526.18
0065	29	21	-624.08	-226.05	-6.93	-63.54	183.85	334.60
0066	30	21	745.87	10.50	43.88	-0.00	-274.91	65.79
0067	30	19	-745.87	-10.50	-43.88	0.00	0.00	0.00
0068	31	19	0.00	-0.00	-0.00	0.00	0.00	-0.00
0069	31	22	-0.00	0.00	0.00	-0.00	-0.00	-0.00
0070	32	23	-1.53	2.37	3.19	0.90	-24.39	15.36
0071	32	24	1.53	-2.37	-3.19	-0.90	-29.84	25.00
0072	33	23	2.37	-1.53	3.19	-24.39	0.90	15.36
0073	33	50	-2.37	1.53	-3.19	24.39	-64.70	-46.05
0074	34	24	-2.37	1.53	-3.19	-29.84	-0.90	25.00
0075	34	48	2.37	-1.53	3.19	29.84	64.70	5.69
0076	35	25	-6.97	0.00	8.30	49.45	-62.28	15.80
0077	35	26	6.97	-0.00	-8.30	-49.45	-78.86	-15.80
0078	36	25	0.	-6.97	8.30	-62.28	49.45	15.80
0079	36	49	0.	6.97	-8.30	62.28	-70.21	-33.24
0080	37	26	0.	6.97	-8.30	-78.86	-49.45	-15.80

Table 2 (Cont'd)

0081	37 47	0.	-6.97	8.30	78.36	70.21	33.24
0082	38 28	576.88	-7.23	24.39	63.53	-45.43	-57.75
0083	38 47	-576.88	7.23	-24.39	-63.53	-174.08	-7.29
0084	39 49	543.80	66.53	-31.01	63.53	75.75	343.41
0085	39 28	-543.80	-66.53	31.01	-63.53	172.31	183.33
0086	40 47	3.17	-2.37	1.53	5.69	-32.14	-68.26
0087	40 48	-3.17	2.37	-1.53	-5.69	29.84	64.70
0088	41 49	-3.19	2.38	-1.54	-46.05	-22.08	68.26
0089	41 50	3.19	-2.38	1.54	46.05	24.39	-64.69
0090	42 49	-181.10	102.29	-19.51	-8.61	201.99	422.70
0091	42 30	181.10	-102.29	19.51	8.61	-123.95	-13.54
0092	43 30	-181.10	102.29	-19.51	-8.61	123.95	13.54
0093	43 31	181.10	-102.29	19.51	8.61	22.40	753.64
0094	44 31	-102.29	181.10	19.51	22.40	8.61	753.64
0095	44 32	102.29	-181.10	-19.51	-22.40	-164.71	695.15
0096	45 32	-138.53	256.18	72.17	22.40	82.90	-428.00
0097	45 33	138.53	-256.18	-72.17	-22.40	-191.15	812.27
0098	46 36	-86.31	30.97	-36.24	-171.07	156.12	322.25
0099	46 32	86.31	-30.97	36.24	171.07	220.89	0.
0100	47 28	-86.58	31.83	33.08	-41.13	-177.73	0.
0101	47 36	86.58	-31.83	-33.08	41.13	-157.20	322.25
0102	48 34	-185.23	47.83	-75.27	191.15	323.48	-620.94
0103	48 33	185.23	-47.83	75.27	-191.15	-22.40	812.27
0104	49 34	47.83	-185.23	-75.27	323.48	191.15	-620.94
0105	49 51	-47.83	185.23	75.27	-323.48	373.37	-763.30
0106	50 51	0.01	451.05	255.72	-278.82	-383.58	676.58
0107	50 52	-0.01	-451.05	-255.72	278.82	0.00	-0.00
0108	51 38	-451.05	-255.72	-0.00	0.	0.00	-104.76
0109	51 52	451.05	255.72	0.00	0.	0.00	-278.82
0110	52 39	-513.76	69.91	0.00	0.00	-0.00	293.00
0111	52 38	513.76	-69.91	-0.00	-0.00	-0.00	-104.76
0112	53 40	-499.76	-138.12	0.00	-0.00	-0.00	-0.00
0113	53 39	499.76	138.12	-0.00	0.00	0.00	-293.00
0114	54 43	-636.29	-207.89	-75.27	10.21	-164.94	-30.24
0115	54 51	636.29	207.89	75.27	-10.21	353.10	-489.48
0116	55 41	-473.30	-119.18	-42.58	-137.09	-101.68	-107.34
0117	55 43	473.30	119.18	42.58	137.09	250.72	-309.78
0118	56 47	4.86	-568.37	-35.90	-235.07	-202.00	-46.22
0119	56 41	-4.86	568.37	35.90	235.07	255.84	-806.34

Table 2 (Cont'd)

0120	57	41	449.19	-478.15	-6.69	154.16	147.99	-913.68
0121	57	42	-449.19	478.15	6.69	-154.16	-127.93	-520.77
0122	58	43	-88.71	-162.99	-32.68	85.78	147.29	-340.02
0123	58	44	88.71	162.99	32.68	-85.78	-0.22	-393.43
0124	59	42	616.44	224.52	-6.69	-56.86	192.09	520.77
0125	59	44	-616.44	-224.52	6.69	56.86	-166.62	334.18
0126	60	44	735.47	9.46	-39.37	0.00	246.65	59.25
0127	60	45	-735.47	-9.46	39.37	-0.00	0.00	0.00
0128	61	45	0.00	-0.00	0.00	-0.00	-0.00	-0.00
0129	61	46	-0.00	0.00	-0.00	0.00	0.00	-0.00
0130								

$$\theta = \arctan\left(\frac{M_y}{M_z}\right)$$

The shear stress acting at this location is

$$\tau = \frac{Tc}{J} \pm \frac{V_y Q_y}{I_y t} \pm \frac{V_z Q_z}{I_z t}$$

with Q_y and Q_z calculated for $y = r \sin \theta$ and $z = r \cos \theta$.

The critical stress based on the maximum energy of distortion theory is

$$\sigma_{cr} = \sqrt{3\tau^2 + \sigma_d^2}$$

This is the stress to be used for comparison to the uniaxial yield stress of the material to determine the elastic limit.

The member of the wheelchair structural system under highest stress in the forward facing position is the upper horizontal strut of the foot rest, member 27 at joint 17. The values of the internal loads (from Table 2) are

$P = 453.6$ lbs

$V_y = -484.6$ lbs

$V_z = 6.9$ lbs

$T = -168.2$ in lb

$M_y = -162.0$ in lb

$M_z = -927.5$ in lb

Using the formulas presented above gives a stress of $\sigma_{cr} = 42{,}500$ psi resulting from an applied load of 1000 pounds. This stress used to determine the yield load as described in the next section.

3.0 EVALUATION OF ELASTIC AND ELASTIC-PLASTIC LOAD RANGES

3.1 Elastic Load Range

The critical stress calculated for member 27 represents the maximum stress in the wheelchair. As long as this stress is below the material yield point, the entire wheelchair structure is in the elastic range of the material. Based on the assumptions of linear behavior, the yield load is calculated by increasing the applied load by the ratio of the yield stress to the critical stress.

$$P_{yield} = P_{applied} \left(\frac{\sigma_y}{\sigma_{cr}}\right)$$

The material used in the wheelchair structure is 1010 steel with a yield stress of

$$\sigma_y = 45{,}000 \text{ to } 55{,}000 \text{ psi}$$

The elastic load limit for the forward facing position is between

$$P_{elastic} = 1000 \left(\frac{45{,}000}{42{,}500} \right) = 1060 \text{ lbs}$$

and

$$P_{elastic} = 1000 \left(\frac{55{,}000}{42{,}500} \right) = 1300 \text{ lbs}$$

3.2 Elastic - Plastic Range

The elastic-plastic behavior is calculated by limit analysis. This theory is based upon the following assumptions.

1. The material behavior is elastic-perfectly plastic, i.e., after the yield point is reached the stress does not increase with increasing strain.

2. The strain in members under bending is proportional to distance from the centroid of the section.

3. The maximum load a structure can withstand is reached when a plastic hinge will cause collapse of the structure.

The wheelchair limit analysis is simplified since the critical stress occurs in a member which does not have redundant support. Thus, a fully plastic moment at the upper foot rest member will cause collapse of the entire chair. The elastic plastic limit corresponds to the load at which a plastic hinge develops in member 27.

A fully plastic moment for a circular tube is

$$M_p = 2\,\sigma_y\, A\,\bar{y}$$

where σ_y = yield stress

$A\bar{y}$ = (area times centroid) = $\frac{2}{3}(r_o^3 - r_i^3)$

therefore $M_p = \frac{4}{3}(\sigma_y)(r_o^3 - r_i^3)$

M_p (minimum) = 1506 in lb

M_p (maximum) = 1840 in lb

The load which would cause an M_p to develop can be approximated by applying the ratio of the fully plastic moment and the moment obtained from linear computer analysis to the 1000 pound applied load.

$$P_{elastic} = P\left(\frac{M_p}{M}\right) \quad \text{where } M = \sqrt{M_y^2 + M_z^2}$$

$$M = \sqrt{(927.5)^2 + (162.0)^2} = 941.5 \text{ in lb}$$

This technique gives a collapse load for the wheelchair in the forward facing position of

$$P_{limit} = 1000 \left(\frac{1506}{941.5}\right) = 1599 \text{ in lbs}$$

and

$$P_{limit} = 1000 \left(\frac{1840}{941.5}\right) = 1954 \text{ in lbs}$$

These calculations are accurate only if the failure occurs in the member itself and not in the joint. The critical location occurs near the slip joint attachment of the foot rest to the wheelchair frame. This region was not simulated precisely in the model; however, the detail required is beyond the scope of the present effort and the assumption was made that the joint is stronger than the parent member.

The second major inaccuracy of the method is in the use of $\sqrt{M_y^2 + M_z^2}$ as the applied load. The effect of torsion, axial load and shear have been neglected. Limit analysis, when applied to simple beams, accounts for these secondary loads by decreasing the fully plastic moment of the section in proportion to the area required to carry the secondary loads. However, the effect of the secondary loads in the wheelchair is small and has been neglected.

Analysis of the inelastic range by use of full theory of plasticity requires much more complex modeling and a nonlinear finite element program. These tools are available but are extremely expensive and were not justified for this analysis.

4.0 COMPARISON OF ANALYSIS AND TEST DATA

4.1 Elastic Range

The static test most appropriate for comparison with the analytical study is test 1045A (a static test of the chair used in Test 1045). The chair was mounted in the forward facing position and tipped with the foot rests contacting the platform. The forward T-bar securement system was used in the test. The load was applied through the seat belt attach points. Data included seat belt load and platform movement.

Figure 5 presents the seat belt load versus wheelchair displacement for the test. From this data an elastic limit of 1300 pounds is obtained. This agrees with the value calculated for the yield stress of 55,000 psi. The value calculated for a yield stress of 45,000 is 1060 lbs or 81% of the test value. According to the test report "the upper footrests buckled at the top" which is the location predicted by the analysis.

Test 1060 simulated the securement system when tested at 19.3 mph. The data obtained were the sled deceleration, the T-bar bolt load and belt tension. The seat belt load defines the input load to the stress analysis. The maximum belt load for test 1060 was 850 pounds which is well below the predicted elastic limit of the system. The test report indicated "minor damage to the front castors and frame" which supports the analytical prediction of no inelastic action. The data are not conclusive enough to state that dynamic response is adequately predicted by analytical methods.

4.2 Elastic-Plastic Range

The static test (1045A), Figure 5, shows a collapse load of 1600 lbs. The equivalent analytic values are 1600 lbs for 45,000 psi yield stress and 1950 lbs for a 55,000 psi yield. The lower value agrees well but the upper value is 22 percent high. The analysis predicts the load within the range of the material property values in both the elastic and the elastic-plastic ranges.

4.3 Deceleration Limit Values

The wheelchair and occupant behave as a decoupled system since the chair stops before the occupant starts deceleration. Therefore the deceleration limit is a function of the stiffness of the occupant restraint system and the wheelchair structure and does not depend on the deceleration pulse of the vehicle or the wheelchair. The deceleration values felt by the occupant are obtained by

$$g's = \frac{F}{W}$$

where

F = the seat belt load
W = weight of acting mass

The collapse limit of the seat belt load ranges between 1600 and 1950 pounds. The weight of the acting mass is determined from the data as follows. Test 1060 data showed a chest deceleration

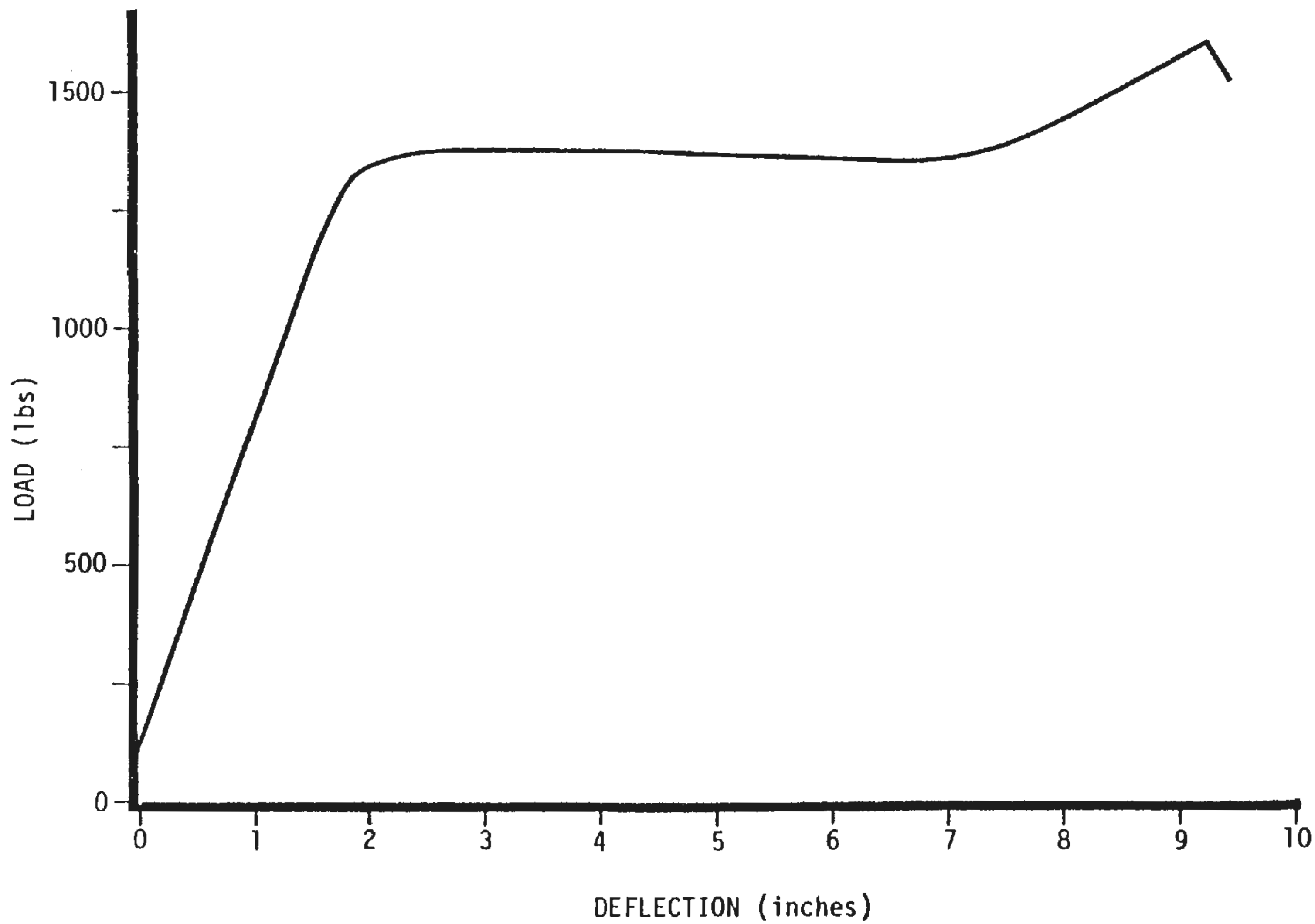


Figure 5. Test 1045A - Static Test of T-bar Securement System

of 7.5 g's for a seat belt load of 850 pounds indicating an acting mass of 113 pounds. Applying this acting mass to the elastic limit load of 1300 lbs gives a minimum chest acceleration of 11.5 g's. The chest deceleration at the maximum collapse load is 17.3 g's.

These g levels represent the deceleration of the forward motion of the occupant. Higher values will be obtained from head and chest impacts into knees or other objects but they are not affected by the wheelchair securement system.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Task 1: The wheelchair structure securement system and test data were inspected. The forward T-bar securement system in the forward facing position fails in the upper foot rest area. Under static test the foot rest shows initial yielding at 1300 pounds seat belt load and total collapse at 1600 pounds. The dynamic test did not load the wheelchair to the elastic limit but some minor damage to the casters and frame was noted.

Task 2: The linear static stress analysis indicated a stress at a critical location at the upper footrest member with a stress of 42,500 psi under a 1000 pound seat belt load.

Task 3: By linear proportioning of the results of Task 2 the upper limit of the elastic load range was established as between 1060 and 1300 pounds of seat belt load. This corresponds well with the test value of 1300 pounds. The chest decelerations related to these belt loads are 9.4 and 11.5 g's.

Task 4: Limit analysis of the critical member indicated a collapse load between 1600 and 1950 pounds. The corresponding static load was measured at 1600 pounds. The chest decelerations under these belt loads are 14.1 and 17.3 g's.

Task 5: The failure mechanism is plastic hinge formation at the upper footrest support.

The above conclusions are based on linear static analysis of the wheelchair structure. They are accurate up to the elastic limit of the material.

The evaluation of structural behavior beyond the elastic limit is much more difficult. The finite element program must be capable of geometric update of the node point location and include a flow theory for the post elastic range. The limit load analysis used here was developed for frame structures in civil engineering. It was intended originally as a method of improving the evaluation of the factor of safety. Accuracies within 25% are reasonable using this method.

The accurate prediction of dynamic response in the inelastic range is much more difficult than just static analysis. Minicars has developed techniques for reliable dynamic response calculation of automobile in crash environments. Similar methods could be applied to the wheelchair problem but they involve both static and dynamic testing to provide necessary data. The methodology is as follows:

1. Dynamic test a structure and observe failure modes.

2. Static test a structure for the same failure modes and obtain force-deflection data.

3. Prepare a lumped mass model and combine with force deflection data.

4. Run computer model at the desired speed ranges to develop the response curves.

Step 1 of this procedure may not be necessary for the wheelchair problem since the inertia loads of the structure itself are small compared to the inertia load of the dummy. Thus, the dynamic failure mode should be the same as a restrained static failure mode.

5.2 Recommendations

To accurately predict the dynamic limits of the wheelchair securement system a combination of test and analysis is required. The program should include:

1. Three static pull tests with force-deflection data for all major load paths.

2. Construct a simple lumped mass model including the dummy as two masses.

3. Run computer simulations for 5 mph increments up to 30 mph.

4. Conduct three dynamic tests at two speeds to validate model. Data must include dummy head and chest accelerations as well as seat belt loads and high speed photography. The predicted failure locations should also be strain gaged.

* U.S. GOVERNMENT PRINTING OFFICE: 1983-0-381-428/3012