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IMPROVING THE SAFETY PERFORMANCE OF PASSENGER RAIL CAR GLAZING SYSTEMS

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ABSTRACT

A review of past accident data shows that several fatalities have been attributed to passenger ejection through window openings during passenger train accidents. To study and address this issue, literature review and accident analyses were performed to investigate the safety aspects of passenger rail window glazing. A common failure mode is when the external gaskets that hold the glazing pane in place shear off and the windows are pushed inside the carbody during rollover derailments. This leads to passengers being ejected, often fatally, out of the train. Passenger containment was identified as the main improvement to be made to glazing systems. New or updated retention methods are thought to be necessary in the pursuit of safety.

Considering feasibility, implementation time, likelihood of success, and the potential for retrofit, a few concepts including various methods of zip-strip protection, a revised zip-strip location, and recessed window glazing have been ideated and the top rated concepts are being developed further.

In the next phase of work, field tests and additional analyses will help determine the efficacy of the proposed solutions and the necessity for additional engineering design requirements.

INTRODUCTION

Over the last 44 years, at least 25 fatalities have been attributed to glazing failure and subsequent passenger ejection through window openings during passenger train accidents. Thus, there is a need to address this issue as part of the rail industry's focus on safety.

Glazing systems on passenger rail cars serve a number of critical functions beyond simply allowing passengers to visually see outside the car. They also must serve the safety functions of: impact resistance, emergency egress, emergency access, fire resistance, and occupant containment, as well as several other performance requirements that are not safety specific.

Design and performance aspects of these functions are covered by standards and regulations by various organizations such as the Federal Railroad Administration (FRA), Association of American Railroads (AAR), American National Standards Institute (ANSI), as well as other procurement-specific requirements. Furthermore, other performance requirements, including optical performance, abrasion resistance, weather resistance, and installation and maintenance requirements are also specified in these documents.

This effort has studied the issues through the following steps:

a. A review of the history of accident performance
b. A review of global design and performance standards
c. Development of potential concepts for improving performance, and
d. Development of potential concepts for test and evaluation

The paper describes the above effort, starting with a review of relevant accident history, followed by an overview and classification of glazing systems.

ACCIDENT HISTORY

To better understand accident failure modes, relevant accidents involving passenger car derailments were studied. The findings from this study formed the basis for further research into passenger car glazing. A few notable accidents are presented here.

Crescent City, Florida – April 18, 2002

This accident involved a derailment of an Amtrak passenger train due to a track buckle [1]. The train subsequently slid across the ground on its side resulting in four fatalities and two serious injuries. These six passengers were found either partially or fully outside of the train after the derailment, leading to the conclusion of inadequate passenger containment by the glazing systems.

Figure 1. Result of derailment and roll-over accident in Crescent City, Florida

Bronx, New York (Spuyten Duyvil) – December 1, 2013

This accident involved a Metro-North passenger train derailment due to excess speed around a curve [2]. This happened as a result of improper train handling by the engineer. Four fatalities and 61 injuries were reported.

Many of the train cars slid on their sides in the direction of travel, and window glazing detached from the cars (Figure 2). Due to the extent of dirt and plant matter in the train and the locations of the four fatally injured passengers, it was concluded that all four were completely or partially ejected from the train through window openings. Two of the seriously injured passengers also sustained injuries consistent with contacting the ground as the cars slid along the ballast.

Figure 2. Result of derailment in Spuyten Duyvil, NY

Cimarron, Kansas – March 14, 2016

On March 14th 2016 an Amtrak train, the Southwest Chief, derailed in rural Kansas. Four cars derailed, flipped on their side, and slid along the ground. The cause of the accident appears to be a misaligned rail. There were 32 injuries reported, but no fatalities and no passengers were ejected.

Figure 3. Zip-strip and gasket condition after Cimarron accident

In all the accidents examined, the main factor which contributed to passenger injuries and fatalities seemed to be the outer gaskets failing during roll-over derailments after being dragged along the ground. Once the gasket has failed, the window pops into the car and leaves an open space and the potential for occupants to be ejected.

OVERVIEW OF GLAZING SYSTEMS

In general, glazing systems may be classified according to:

1. Glazing materials
2. Glazing assembly
3. Glazing framing/Mounting method
4. Exposure/Aspect
5. Mechanisms for emergency egress
6. Mechanisms for rescue access

These are detailed below.

1. Glazing Materials

The two most prevalent glazing element materials (individual sheets) used in bodyside passenger rail windows are:

a. Polycarbonate
b. Treated glass

Polycarbonate materials offer better impact performance than untreated glass, plus a weight advantage. These materials are often sold under brand names such as Lexan or Makrolon.

Treated glass is usually heat treated (tempered or toughened) to improve strength and failure properties.

Individual sheets of glass might be bonded together with an intermediate polymer layer, such as PVB (Polyvinyl Butyrate) or EVA (Ethyl Vinyl Acetate) to form sheets of laminated glass that offer improved strength, insulation, and UV reduction properties.

2. Glazing Assemblies

Most modern railroad glazing designs do not use a single sheet of glazing, but have shifted towards composite construction with multiple layers. It is common to see windows that have two separate panes of glass with an air interlayer; often one or both of the glass layers will be tempered or laminated. Some commuter and transit agencies, however, continue to use single layers.

These composite assemblies come in many variants and are usually the result of the experiences and expectations of individual railroads, in terms of functionality. For example, on its Superliner cars, Amtrak uses windows that are composed of dual-pane, ¼” thick transparent, monolithic polycarbonate glazing sheets with a ¼” gap, held together by an aluminum perimeter frame. On the other hand, MetroNorth and NJ Transit use a single pane of polycarbonate glazing that is 0.46” thick.

3. Glazing Framing and Mounting

Most glazing assemblies are first installed in a floating perimeter frame, which is then mounted to the car body. Common methods of attachment of the glazing assembly to the car frame include:

a. *Gaskets and Seals*, wherein, the glazing assembly is held in place on the car shell using either single or multiple elastomeric seals; there are no adhesives, bonding agents, or mechanical fasteners used. This is common on several US railroads. Elastomeric zip strips are used to allow for easy installation and for emergency egress and access reasons. They consist of a rubber seal with a detachable inner section of the same material; once removed, the outer rubber is able to deform and allow egress and access.

b. *Bonded applications*, involve the use of adhesives to bond the glazing assemblies to the carbody. In these applications the glazing assemblies are usually connected to either framing elements or gasket elements, which are then adhesively bonded to the car structure. The glazing can still be removed by emergency responders.

c. *Fastened applications*, use mechanical fasteners (screws, bolts, nuts) to attach the glazing frame to the carbody. These are uncommon in the US due to rescue access regulations, but NYCT subway cars use a similar approach to address their anti-vandalism needs.

d. *Clamped systems* use a mechanical clamping system to attach the window framing to the car structure. These are relatively rare in railroad applications. While these systems offer the potential for alternate forms of window removal under emergency conditions, in reality, the clamping mechanisms are likely too complex for use by regular individuals under emergency conditions.

4. *Exposure/Aspect*

Section 3 discussed the specific methods of mounting the glazing system to the carbody. Another element of this is whether the mounting results in a protruding aspect or a flush/recessed aspect.

Several US designs, as well as a few European metro car designs, have adopted a protruding aspect, where a portion of the gasket and the exterior window surface are outside of the carbody envelope (Figure 4). Under this protruding aspect, the glazing systems are likely to have a higher exposure to prying and normal forces under derailment conditions, and thus are more likely to separate. This was true of the Amtrak bi-level Superliner cars in the Crescent City, FL and Cimarron, KS accidents, as well as the Metro North single-level typical commuter cars in Spuyten Duyvil, NY.

Other designs present a recessed or ‘flush’ aspect, wherein the sealing method and the glazing are less exposed to derailment forces. This aspect may be achieved by either moving the window mounting inwards, or having features wherein, the entire window area is effectively ‘recessed’, by having other elements of the car shell that are protruding beyond the window surface (as in the older SEPTA cars). Most modern high-speed rail equipment has recessed/flush windows.

Figure 4. Protruding aspect (left); Recessed aspect (right)

5. Emergency Passenger Egress

In general, two primary approaches are utilized for providing emergency egress.

a. For most US applications, egress is provided through the use of a zip strip that is installed with a pull handle on the interior side of the window. Usually, a red, conspicuous handle is provided for this purpose (Figure 5).

b. Another option is to provide special tools in the car, which can be used to break the glass at a pre-determined spot and create an opening. In the UK, the MK III vehicles are fitted with double glazed units of toughened glass that would each be breakable to provide a means of escape, by using tools supplied in the car. Chinese passenger rail cars similarly employ the model of having passengers use an instrument to break specifically designated windows in case of emergency. No zip-strips are used in either country.

We know from accident reports that glazing typically does not shatter during rollover accidents. Often times the intact glass is found pushed inside the cars, leaving an opening in the bodyside. This reason leaves open the potential for tools to be used to break the glazing for access or egress.

Openable windows are not generally used in modern rail passenger cars; however, they may be used on cab windows with only train crew access. Under emergency conditions these openable windows may be accessible to passengers under the direction of train crew.

Figure 5. Zip-strip (left); openable cab window (right)

6. Emergency Rescue Access

Similar to emergency egress options, the two most common methods of rescue access are zip strips and breakable glass.

a. In the US, zip-strips are the prevailing means of emergency access from the exterior of a passenger car. Once the zip-strip is removed, the window can be pushed in to allow access by emergency responders.

b. In the UK and in some other applications, emergency responders can break the glazing from the outside to provide rescue access. Rescue workers have access to tools such as sledgehammers, glass cutters, and other implements that facilitate quickly breaking the glass. Tempered glass and laminated glass are designed to shatter in a manner that reduces the possibility of injury to trapped passengers. Even in the US, if removing the zip-strip is not possible for any number of reasons, breaking the glass using available tools is an option for emergency personnel.

REGULATIONS, STANDARDS, AND REQUIREMENTS

Glazing systems on passenger rail car side windows serve a variety of safety critical functions such as:

- Impact resistance (both ballistic and large object)
- Emergency egress (car occupants being able to get out of the car)
- Rescue access (for emergency personnel trying to enter the car)
- Occupant containment
- Smoke and Flame resistance

From an impact resistance perspective, most current regulations focus on the performance of the individual glazing panes themselves, rather than on the glazing unit as a whole system. This approach is not representative of what is likely to happen in an accident scenario. Previous accidents have shown that more often than not, the strength of the glazing panes is not the determining factor in the outcome of passengers' safety.

Emergency egress and rescue access requirements are outlined by the FRA through 49CFRPart 238. Other global standards specify similar requirements.

None of the global standards, with the exception of GM/RT 2100 (see below), appear to specify occupant containment requirements. In general, requirements for occupant containment or overall strength of the glazing system are not considered in the design effort, beyond considerations for air pressure loads from high-speed operations. In some cases, reduced exposure to derailment loads has been achieved by either recessing the glazing system within the carbody, or by recessing the window area.

One exception to the above global approach has been recently-adopted requirements from the UK (under GM/RT 2100) [3]. This standard, implemented in 2010, prescribes a detailed set of requirements for the strength of the glazing system (including the gaskets and not the glazing pane only), consisting of a series of physical tests with pass/fail criteria. The criteria evaluate the strength of the glazing system under external and internal forces that might be experienced in derailment conditions.

Specifically, GM/RT 2100 prescribes the following sequence of tests. The impact of a steel ball weighing about 11 lbs. and traveling about 21 mph, and then an impact using a pendulum with an impact energy of 589 joules, and finally a concentrated load of 0.8 kN on the interior surface. The glazing must pass all three tests in succession with no penetration and minimal spall.

Another key element of this UK approach is that it trades the global approach for emergency egress provisions with the requirement for passenger containment. Rescue access is expected to be provided by trained emergency personnel with the tools needed for quick glazing dis-assembly. In other words, the GM/RT 2100 standards contend that it will be safer for occupants to stay within the vehicle, until rescued by emergency personnel. However, given the past history of vehicle interior fires, this approach will probably not be considered acceptable in North American service.

Smoke and fire requirements are defined at the material level by 49CFR Part 238 and other referenced ASTM standards covering test requirements.

Based on the above, the project team compiled a list of existing requirements for glazing systems from both regulations and industry practices, plus, it has proposed a draft set of additional requirements to improve glazing system performance under accident conditions, essentially addressing occupant containment requirements. The proposed occupant containment requirements are described further in the section on test methods.

In addition, the following functional requirements were also considered and included by the research team: optical quality, dimensional stability, flexibility, fracture and impact characteristics, gasket hardness and mechanical properties, environmental resistance, durability, corrosion resistance, ease of maintenance, and anti-vandalism properties.

ACCIDENT MODELING AND SIMULATIONS

To understand under what forces glazing separation will occur, several simulations were performed. These attempted to replicate internal and external forces likely to be experienced in an accident.

The finite element (FE) models were developed using HyperMesh [4], a finite element pre-processor that generates the geometry and the mesh representations. Simulations were performed using LS-DYNA [5, 6], a multi-purpose explicit and implicit finite element program used to analyze the nonlinear response of structures. It has a long history of application in crashworthiness, blast and impact response, occupant and pedestrian safety analysis, and other related problems.

The developed FE models include (Figure 6):

- Metal frame representing the outside sheet of the passenger car
- Rubber gasket
- Lock strip (zip-strip)
- Laminated glass

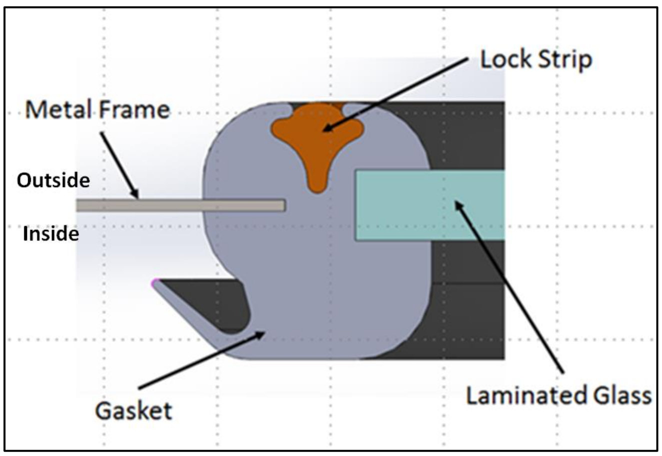

Figure 6. Components of the FE model

These finite element models were used to estimate the internal and external forces and likelihood of glazing retention failure under a variety of accident conditions, including:

- Rollover impact on an abrasive surface
- Projectile impact from a steel ball
- Human body/Anthropomorphic Test Device (ATD) impact onto the inside surface of glazing
- Externally applied derailment loads

The modeling effort demonstrated the significant difficulties and uncertainties associated with modeling highly non-linear materials such as glass, laminations, rubber, and elastomers. A detailed description of the modeling effort is outside the scope of this paper and will be discussed in detail in a future paper.

POTENTIAL DESIGN CONCEPTS

The challenge of this project is to identify mechanisms to improve the containment performance of glazing systems without compromising on the emergency egress and rescue access requirements. Naturally, any endeavor to improve glazing system performance should pay particular regard to the fact that these systems are expected to perform several potentially conflicting, safety-critical functions, including:

- Providing a clean and unobstructed view
- Withstanding a variety of loading conditions
- Providing impact protection from potential projectiles
- Containing occupants and crew during an accident
- Allowing for rapid egress and rescue operations

As an example, the system needs to be strong enough to provide protection from large object impact and aerodynamic forces, while at the same time being easy to remove by potentially injured passengers in an accident. In addition, there are other practical considerations such as manufacturing, installation, weight and cost. Given the competing expectations for glazing system performance, any efforts to revise the requirements, the design, or the evaluation procedures need to be grounded on a solid technical basis.

Considering the constraints, several ideas for improving glazing performance were developed and evaluated based on their likelihood of success. The ideas which rated highly were further developed into concepts. These concepts are likely to undergo further revision based on the results of the next phase.

Shown below are six concepts to improve the occupancy containment during derailments, along with the currently used design. The concepts still allow for egress, fire protection, and improved containment. Emergency access from outside is possible but further design evaluation is required.

Presented first (on the left in Figure 7) is the current design, which uses an outer zip-strip. As can be seen, the outer gasket - especially the zip-strip - is exposed and susceptible to being torn off during an accident. The first new concept involves the use of a clip similar to what is used on car hubcaps (seen in green in the right of Figure 7). The clip is made of metal and would protect the outer gasket during an accident. The clip replaces the locking strip. It can be pried loose and pushed in by emergency personnel.

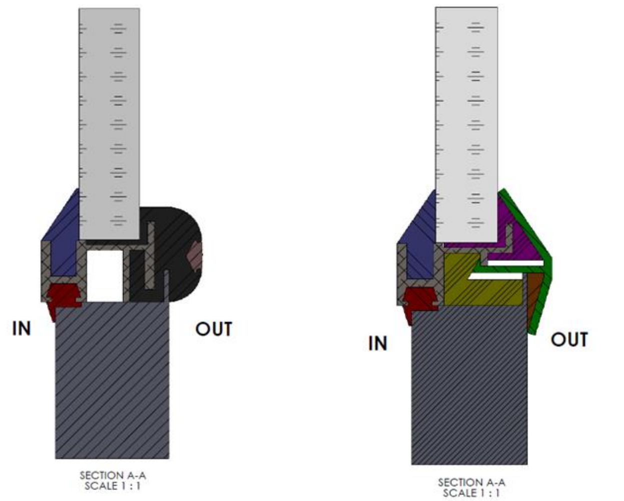

Figure 7. Existing design (left) and new concept 1 (right)

The second concept will use the existing design but relocate the outer zip-strip to a more favorable position. In this configuration, the zip-strip is subjected – in theory - to lower shearing forces during an accident. See the left image in Figure 8; the relocated locking -strip sits on the top part of the gasket.

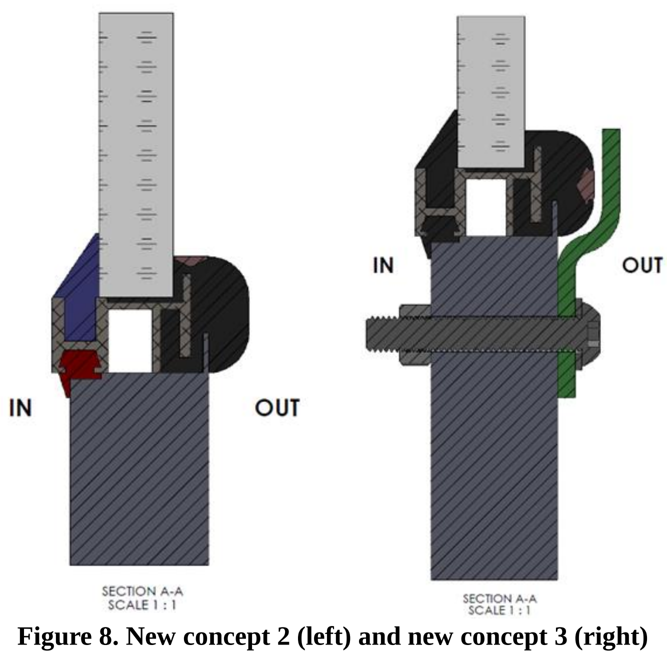

Figure 8. New concept 2 (left) and new concept 3 (right)

Concept three (Figure 8, right) involves mechanically fastening a metal piece over the outer gasket and zip-strip. This way, there is a reduced likelihood of the zip-strip becoming dislodged during an accident. One of the main benefits of this design is the ease of retrofitting existing railcars.

The fourth design concept (Figure 9, left) is to effectively recess the glazing system within the carbody slightly by installing a metal frame surrounding the glazing system. During a rollover accident, the gasket and zip-strip are likely to experience lower forces and are more likely to remain in place. The value of 3 inches seen in the figure is only a placeholder and more research would likely be necessary to determine the optimal value.

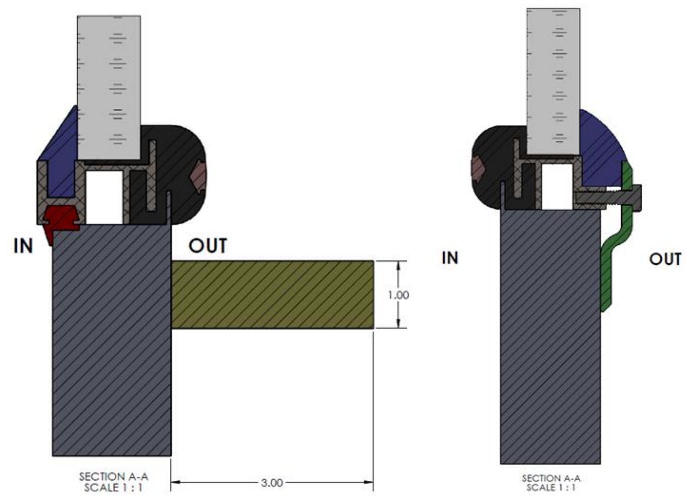

Figure 9. New concept 4 (left) and new concept 5 (right)

The fifth concept (Figure 9, right) utilizes an inner zip-strip with an outer gasket protected by a mechanically fastened metal sheet. The gasket can be pried open by emergency personnel. The inner zip-strip can be removed by passengers.

The sixth concept (Figure 10) uses a metal cap welded to the carbody to protect the gasket and zip-strip during a rollover. It may be possible to choose the material for the cap in such a way that it crumples around the zip-strip during an accident and further increases safety performance. In an emergency situation, responders must pry up the metal cap and then remove the zip-strip.

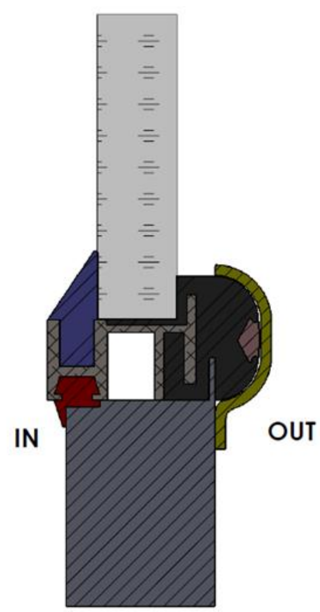

Figure 10. New concept 6 – welded zip-strip cap

Another design idea discussed was to separate the FRA requirements for emergency egress and emergency access. The FRA requires four windows per car to have emergency egress capabilities. Similarly, the requirement for emergency access from the outside is two windows per car. Instead of having all windows use the same design, a safer option may be to optimize which windows have which capabilities. Some windows would be for emergency egress, and some for emergency access, but not both capabilities in one window. This will ensure that most of the windows have the maximum occupant containment capacity.

TEST METHODS

In addition to developing concepts for improving the performance of glazing systems, the research team has also considered and developed concepts for effectively testing glazing performance for occupant containment. The proposed occupant containment tests for the glazing system (defined as the glazing, all associated gaskets and zip strips, and relevant parts of the car structure) are as follows:

1. The glazing system shall withstand a uniform load of 500 lb/ft^2 applied over the glazing area without failure
2. The glazing system shall withstand a local load of 1500 lb applied over an area of 6 in.^{2}, without failure
3. The glazing system shall survive a shear abrasion test (potentially applied as a rolling tire test on both the gasket and the glazing) without failure
4. The glazing system shall survive a gasket prying test without failure.

These test cases are further described below, using finite element style notations.

Test Case 1

The case simulates a vehicle rollover situation with loading on window system. Figure 11 below shows the applied loads and constraints for this test case. The loads are taken from RSSB T424 [7] except they are slightly more conservative (higher) values.

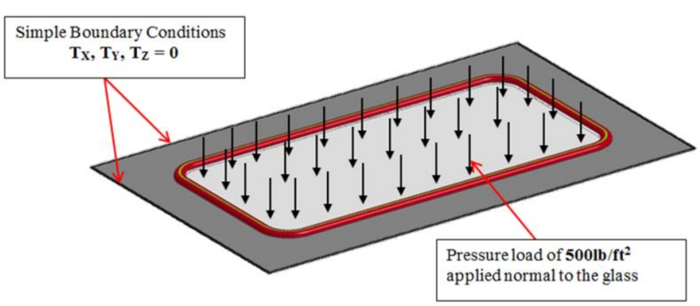

Figure 11. Test case 1

Test Case 2

In this test case, the 1,500lb load is applied on an area of 6in^2. A center area and an edge area should be tested. Figure 12 below shows the applied loads and constraints for this test case. The loads are taken from RSSB T424 except they are slightly more conservative (higher) values.

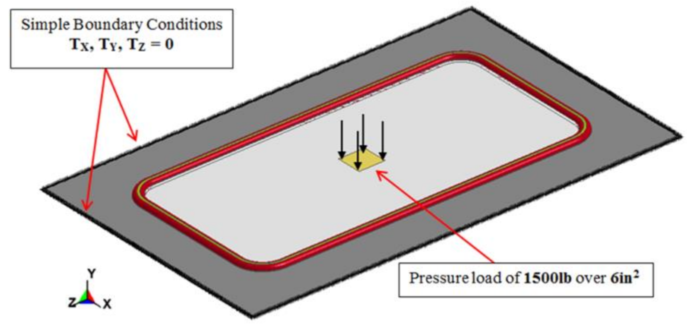

Figure 12. Test case 2

Test Case 3

For this test case, a tire with 2,250lb downward force rolls over the glazing system with the intent of demonstrating the resistance of the system to prying loads experienced during a derailment (Figure 13). This test case can also be a non-rotating object abrading across the surface at 20mph. The loads are taken from RSSB T424 except they are slightly more conservative (higher) values.

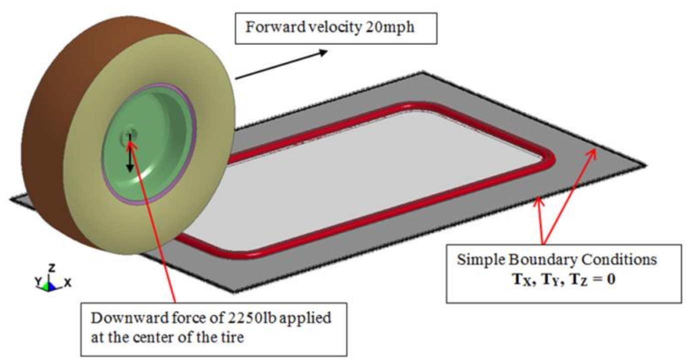

Figure 13. Test case 3

Test Case 4

This test case simulates a rail vehicle rolling over on its bodyside windows. The glazing test panel is dropped from a certain height and tied to a certain mass (the height and mass to be consistent with the energy input from a rollover derailment) and dragged on a simulated ballast-like surface.

The drop and drag test, as shown in Figure 14, aims to simulate the effects of an initial impact and shear forces on the side panel and glazing as a result of derailment. The test requires a consistent, engineered target surface, crane, pulling vehicle, and additional weight on the side panel (if necessary). The test specimen will include one glazing article and a portion of vehicle sidewall panel attached to it as in a passenger car (for instance, 6 inches from each edge). Based on derailment simulation results from LS-Dyna and previous derailment reports, additional weight, specimen drop height, pulling speed, and ballast road length will be determined. Ballast width can be determined based on the specimen size. Ballast surface can be altered to maintain very high friction in order to simulate the worst possible derailment scenario.

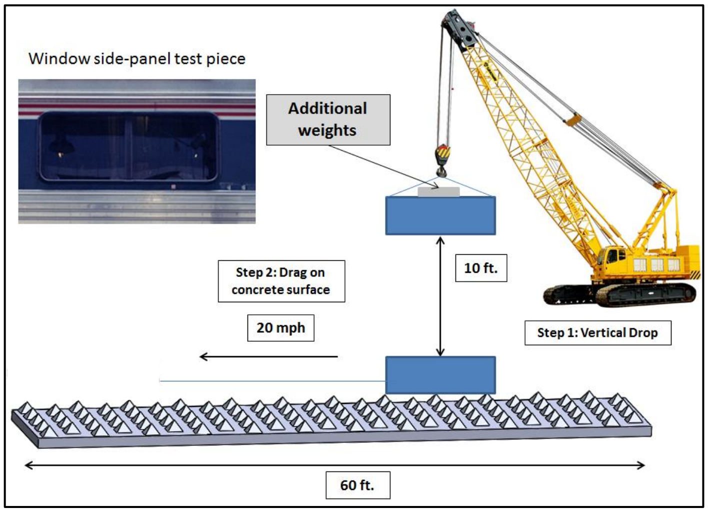

Figure 14. Test case 4

One thought for the target ballast surface is to have a test mold from which consistent concrete surfaces can be made, allowing for multiple tests, as well as repeatability of the test setup.

More research is needed to determine whether the 'drop' portion of test case 4 is necessary. That is, whether it has been shown that the rail car hitting the ground during a derailment has an effect on the glazing, or whether the 'dragging' experience causes all the damage.

Specific implementation methodologies for the test cases are under development and are subject to review based on future research.

Additional methods such as the test sequence outlined in the RSSB research effort detailed above also have potential applicability.

SUMMARY

This paper describes preliminary research efforts on evaluating and improving the performance of passenger railcar glazing systems under accident conditions. As part of the research effort completed so far, the research team has:

- Reviewed the accident performance of glazing systems and identified common failure modes
- Reviewed global standards and designs for glazing systems
- Developed potential new design concepts for improving occupant containment performance without compromising emergency egress or rescue access
- Developed test methods for evaluating the occupant retention potential of glazing systems

The next steps on this effort include pilot prototyping and test efforts to evaluate the performance of the highest ranked concepts.

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