Safety Standard for Structural Requirements for Light Rail Vehicles

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

ASME RT-1–2015

(Revision of ASME RT-1–2009)

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The American Society of Mechanical Engineers
Two Park Avenue, New York, NY 10016-5990

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FOREWORD

On March 18, 1998, The American Society of Mechanical Engineers (ASME) formed the Standards Committee on Rail Transit Vehicles.

The Standards Committee on Rail Transit Vehicles develops and maintains standards that cover safety, functionality, performance, and operability requirements, as well as mechanical systems, components, and structural requirements for rail transit vehicles. Rail transit includes heavy rail and light rail, and excludes freight, commuter, high-speed, or any other rail operations under the jurisdiction of the Federal Railroad Administration.

The Standards Committee is responsible for developing a series of safety standards within its Charter under the designation of RT. The purpose of the RT standards is to provide the rail transit industry with safety standards that address vehicle mechanical systems, components, and structural requirements, so as to enhance public safety. Principles, recommendations, and requirements included in these standards promote good engineering judgment as applied in designing rail transit vehicles for safety. The standards are subject to revisions that are the result of Committee consideration of factors such as technological advances, new data, and changing environmental and industry needs.

Both SI (metric) and U.S. Customary units are used in this Standard, with the latter placed in parentheses. These units are noninterchangeable and, depending on the country as well as industry preferences, the user of this Standard shall determine which units are to be applied. Parameters are derived from IEEE/ASTM SI 10-1997 or the latest revision, with the U.S. Customary units noted in parentheses.

This edition was approved by the American National Standards Institute on September 9, 2015, and designated as ASME RT-1–2015.

ASME RT COMMITTEE
Rail Transit Vehicles

(The following is the roster of the Committee at the time of approval of this Standard.)

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General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to

Secretary, RT Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Interpretations. Upon request, the RT Standards Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the RT Standards Committee.

The request for an interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The RT Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the RT Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at http://go.asme.org/.

INTRODUCTION

(15)

Safety of light rail transit operations is a system characteristic. As do all transportation options in a given corridor, this operation has certain risks, including collision with another vehicle. The risks are mitigated by the design of the signal system and other system elements, by operating and maintenance procedures, and by the design of the vehicle. Risks are further mitigated by the elimination of grade crossings and the provision of safety barriers. Active safety systems on the vehicle include train control, communication, and propulsion and braking subsystems. The carbody, if properly designed, may be considered a passive safety device, and this Standard is intended to address the performance of the carbody in collisions.

This Standard draws from existing requirements and best practices for the design of the carbody of light rail vehicles. It also considers recent developments in the design of rail carbody structures intended to optimize the performance of the structure under the conditions of an overload, as might occur during a collision. This measure is commonly identified as crash energy management (CEM). The intent of CEM is to better manage the dissipation of the portion of the energy of a collision that can reasonably be expected to be absorbed by the deformation of the carbody. CEM design, when appropriately applied, may reduce risk of injuries to occupants of the light rail vehicle due to loss of survivable volume and due to secondary collisions of occupants with the car interior. Specific portions of the carbody are designed for controlled deformation and energy absorption, and are located in the structure so as to limit the damage to, and acceleration of, occupied volumes of the cars of light rail consists. For multiple-unit operation, distributing structural energy absorption through the train has been shown to be beneficial. This Standard requires the incorporation of CEM principles in the design of light rail vehicles.

ASME ASME RT-1–2015
SUMMARY OF CHANGES

Following approval by the ASME RT Committee and ASME, and after public review, ASME RT-1–2015 was approved by the American National Standards Institute on September 9, 2015.

ASME RT-1–2015 includes editorial changes, revisions, and corrections identified by a margin note, **(15)**.

Page	*Location*	*Change*
vii	Introduction	Revised
1	Section 1	Revised
	Section 2	(1) Definitions of *anticlimber*, *articulation*, *average collision acceleration* (formerly *average acceleration*), *belt rail*, *carbody*, *collision posts*, *consist*, *corner posts*, *crash energy management (CEM)*, *crashworthiness*, *end frame*, *end sill compression load (buff load)*, *light rail vehicle*, and *streetcar* revised (2) Definitions of *heavy rail transit vehicle* and *vehicle weights (vertical loads)* deleted (3) Definitions of *coupler system*, *vehicle*, and *vehicle vertical loads* added
3	Section 3	Revised
	Section 4	Revised
4	Section 5	Revised in its entirety
5	6.1	Revised
	Section 7	Revised
	Section 8	Revised
	9.1	Revised
6	9.2	Revised
	9.3	Revised in its entirety
7	10.2	Revised
	10.3.1	Revised
	10.3.2.1	Revised

Page	*Location*	*Change*
8	10.3.2.2	(1) Subparagraph (g) revised (2) Subparagraph (h) deleted and subsequent paragraphs redesignated
	10.3.3.1	Revised
	10.3.3.2	Subparagraph (b) revised
	10.3.4.1	Revised
9	10.3.4.2	Subparagraph (b) revised
	Section 11	Revised
10	Table 1	Revised in its entirety
13	Table 2	Revised in its entirety
16	Table 3	Added
	Table 4	Added

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SAFETY STANDARD FOR STRUCTURAL REQUIREMENTS FOR LIGHT RAIL VEHICLES

(15) 1 SCOPE

1.1 Subjects Covered by This Standard

This Standard applies to carbodies for newly constructed light rail vehicles and streetcars for transit passenger service. The Standard defines requirements for the incorporation of passive safety design concepts related to the performance of the carbody of light rail vehicles in conditions such as collisions, so as to enhance occupant safety and control damage.

1.2 Subjects Not Addressed by This Standard

There are several issues related to safety that are not addressed, such as, but not limited to

(a) structural repairs
(b) fatigue
(c) corrosion
(d) fire protection
(e) interior vehicle design
(f) emergency egress from vehicle
(g) inspection and maintenance
(h) operator seat belt

1.3 Effective Date

This Standard applies to carbodies of newly constructed light rail vehicles and streetcars for transit passenger service ordered 180 days following the date of issuance of this Standard by the RT Standards Committee and ASME.

(15) 2 DEFINITIONS

This Standard relies, where practical, on terms already in use by ASME, the American Public Transportation Association (APTA), and the Institute of Electrical and Electronics Engineers (IEEE). For the purposes of this Standard, the following definitions apply:

anticlimber: a structural member located at each end of the vehicle, used to engage an opposing car or other coupled vehicle to resist relative vertical travel between the two carbodies during a collision.

articulation: a connection sometimes used at the center of a vehicle or at the intermediate ends of carbody sections to allow negotiation of tracks with various vertical and horizontal profiles.

average collision acceleration: the average computed longitudinal acceleration at the vehicle center of gravity. The average computed acceleration is evaluated over the period of time from first contact between colliding vehicles to the time when the contact force between vehicles first returns to a magnitude of zero.

belt rail: a longitudinal structural member of the carbody located on each side of the carbody below the passenger side windows. The belt rail often establishes the overall width of the carbody, exclusive of the side door thresholds and the side cameras and mirrors.

carbody: the vehicle body comprising its main load-carrying structure above all truck suspension units. It includes all components and structural articulation parts, if any, that are connected to this structure and contribute directly to its strength, stiffness, and stability. Mechanical or electrical equipment and other mounted parts are not considered part of the carbody, though their attachment brackets are. The "coupler" ends of the carbody are the outside vehicle ends that contain the means for coupling to another vehicle. The "intermediate" ends, if any, contain the articulation system.

closing speed: the speed of a vehicle relative to another object or vehicle at the time of initial impact.

collision posts: a set of two structural posts located at each end of the carbody, extending from the bottom of the underframe structure up to the structural shelf. Collision posts can be made of several structural members assembled to each other, provided that the required performance is met. They are located at the approximate one-third points across the width of the vehicle, and are forward of the seating position of any passenger or crew person. An alternative to collision posts is the use of a collision wall.

collision wall: a structure at the leading end of the vehicle spanning the area between the structural shelf, corner posts, and top of the underframe.

consist: the makeup or composition of the individual units of a train, generally by number of cars and type of vehicle.

corner posts: a set of two full-height structural posts located at or near the two corners at one end of the carbody, extending from the bottom of the underframe structure up to the roof at the top of the side frame at its intersection with the roof.

coupler system: a system comprised of the coupler head, drawbar, draft gear, and attachments to the carbody, permitting the connection between light rail vehicles or streetcars.

crash energy management (CEM): a method of design and manufacture of vehicle structures that enhances crashworthiness by assigning certain sections of the carbody the task of absorbing a portion of the collision energy by crushing in a controlled manner (see *structural energy absorption zone*). The controlled crushing and energy absorption functions are typically assigned to special carbody structural members in the structural energy absorption zone that are designed to crush in a predictable and stable manner over a distance that depends on the design of the member and the desired amount of energy absorption.

crashworthiness: the ability of a carbody to manage the collision energy while maintaining structural integrity and limiting the level of acceleration, so as to minimize casualties to occupants and pedestrians and damage to other vehicles.

end frame: structure inboard of the extreme ends of the vehicle supporting the anticlimber, corner posts, and collision posts.

end sill compression load (buff load): longitudinal compressive force applied at the ends of the vehicle, usually at the anticlimber.

light rail vehicle (LRV): LRVs operate on a light rail transit system, and are not part of main-line railroads. Light rail vehicles are capable of boarding and discharging passengers at track/street level or elevated platforms. The light rail vehicle is a mode of rail transit characterized by its ability to operate on exclusive rights-of-way, shared street running, and through roadway grade crossings. (See also *streetcar.*)

permanent deformation: for the purpose of design, permanent deformation is a condition resulting from a stress greater than the minimum yield strength of the material, or where the material has deformed to the extent that it will not return to its original shape or position after the load is released. Similarly, when testing a structure, permanent deformation is characterized by a loading condition resulting from physical stress greater than the yield strength of the material, or where there is evidence that the material has deformed to such an extent that it will not return to its original shape or position after loading is removed.

streetcar: a category of LRV that operates mainly at street level in road traffic, normally as single units or two units per train and at a maximum speed of 70 km/h (44 mph). Vehicles are typically smaller, lighter, and narrower in width than light rail vehicles.

structural energy absorption zone: a zone, typically located at the ends of the carbody, designed for controlled deformation or crush when the carbody is loaded beyond its elastic capacity, while the integrity of the remaining carbody is maintained.

structural sheathing: the parts, if any, of the exterior covering of the carbody that are used as structural components of the vehicle and included in the stress analysis.

structural shelf (light rail): the structural member in the end frame that spans the full width of the carbody and is attached to the tops of the collision posts and to the corner posts, and designed to transmit the collision post top reaction loads to the carbody sides.

survival volume: volume of the vehicle body containing the occupants that is maintained during the collision and that is sufficient for their survival without major injury.

telescoping: the intrusion of one vehicle into another in a collision.

ultimate strength: the maximum load-carrying capability of a structure, for a load applied at a specified location and direction. For further deformation of the structure, the load capable of being supported will be less than this maximum load.

vehicle: a complete autonomous ready-to-run light rail vehicle or streetcar that contains all the minimum system requirements for operation, and that may have a coupler or drawbar at each end. The vehicle may be comprised of multiple carbody sections that are connected by articulation joints and allow passage of passengers between sections while in service.

vehicle vertical loads

(a) *ready-to-run:* a vehicle that is service ready with all mounted components, including full operating reserves of lubricants, windshield fluid, etc., but without any crew or passenger load.

(b) *seated load:* ready-to-run load plus the crew and all passenger seats occupied with average weight per person of 79.5 kg (175 lb).

(c) *car volume capacity load:* a seated load plus all available standee areas occupied with a standee density that results in a floor pressure of 488.4 kg/m^2 (100 lb/ft^2).

NOTE: An alternate occupant weight based upon specific service conditions, such as service to airports and use of luggage racks, may be specified.

yield strength: the stress value published by the American Society for Testing and Materials (ASTM) for the specified material and grade. If the material used is not covered by an ASTM specification or another specification, the minimum yield strength for design shall be as guaranteed by the material supplier.

(15) 3 INTEROPERABILITY

This section covers geometric compatibility and crush mechanism design considerations for different vehicles operating on the same routes of the subject transit system.

3.1 Anticlimber and Coupler Interface

Each light rail vehicle shall incorporate an anticlimber at each end of the vehicle. The height and design of the anticlimber and coupler on new light rail vehicles shall be compatible with existing light rail vehicles that are operated on the same routes of the customer's transit system. The anticlimber shall be designed for engagement between vehicles to mitigate override or telescoping in a collision, including any condition of failed or deflated suspension elements. In the event of a collision with another rail vehicle, the coupler system shall include a feature that will permit engagement of anticlimbers. See section 6 for additional requirements.

Design of the vehicle leading end structure shall not interfere with proper engagement or operation of the vehicle anticlimber system.

3.2 LRV and Streetcar Leading End Design for Protection of Street Vehicles

For light rail vehicles and streetcars operating in urban environments sharing roadways and crossings, the design of the leading end of the carbody shall incorporate a contoured geometry shape extending across the width of the vehicle, enclosing open area spaces to encourage deflection of struck objects from the path of the LRV/streetcar and to minimize entrapment, override, and penetration of automobiles and light trucks. Sharp corners and protruding shapes of the contoured geometry design shall be minimized. A bumper, coupler enclosure, pilot beam, skirting, and/or alternative structures may be used to achieve these objectives.

The bottom of the car end structures as described in the previous paragraph, with nominal floor height conditions, shall not be greater than the larger of 250 mm (10 in.) above the top of rail or the minimum allowable by the dynamic operating envelope.

The leading end design shall take into account collision compatibility with automotive construction.

NOTE: Side structures for typical automobiles and light trucks are designed for load-bearing reinforcement at a height above the roadway surface ranging from 250 mm (10 in.) to 635 mm (25 in.). Matching the leading end geometry and structural design of the LRV/streetcar to this height reduces the likelihood of LRV/streetcar penetration into passenger compartments of these vehicles, thus reducing injury propensity. See SAE Paper No. 1999-01-0071.

(15) 4 STRUCTURAL REQUIREMENTS

The carbody shall withstand the maximum loads consistent with the operational requirements and achieve the required service life under normal operating conditions. The carbody design shall be based on the design load requirements specified in section 5. The capability of the structure to meet these requirements shall be demonstrated by calculation and/or appropriate proof-of-design testing. The vehicle is assumed to be of double-end design with an operating cab at either end. If the vehicle is of single-end design, the rear of the vehicle should be of equivalent design and, in a collision, should respond in the same manner as the front end.

The strength of connections between structural members for all structural loading requirements outlined in Tables 1 and 2 shall exceed the ultimate load-carrying capacity of the weakest member joined. For these load cases, the ultimate load-carrying capacity is defined by applying the load at the location and in the direction specified in Tables 1 and 2, but increased in magnitude to the maximum load that can be resisted by the structure, as determined by observing that further increase in deflection will result in a decrease in the load capable of being carried by the structure.

4.1 Welding

Design of welded structures shall be in accordance with AWS D1.1/D1.1M for steel and AWS D1.2/D1.2M for aluminum, or equivalent.

4.2 Articulation

The articulation shall include structure to meet the requirements of section 5.

4.3 Design Parameter Tolerances

The allowable stresses for the loads specified in section 5 shall consider the limiting cases of dimensional tolerances, manufacturing processes, workmanship, and other manufacturing conditions.

4.4 Demonstration of Strength and Structural Stability

It shall be demonstrated by analysis (section 9) and/or tests (section 10) that the requirements of section 5 are achieved.

4.5 Truck-to-Carbody Attachment

A mechanism for attaching the completely assembled truck, including the bolster if used, to the carbody shall be provided, with strength levels in accordance with section 5. The strength of the attachment mechanism loaded in the vertical direction shall be as specified to secure the entire truck to the carbody when the vehicle is raised unless first intentionally detached. The strength of the attachment mechanism loaded longitudinally in a horizontal plane shall be as specified to secure the entire truck to the carbody during collisions at any possible position of the truck in its vertical suspension travel. This shall include the condition of the vehicle raised off the track with the truck hanging from the vehicle, and shall not depend upon external vertical loading nor upon bolster anchor rods. The strength of the attachment mechanism loaded laterally in a horizontal plane shall be as specified to secure the entire truck to the carbody during collisions of roadway vehicles with the side of the light rail vehicle or streetcar.

4.6 Crashworthiness

The carbody shall be constructed in such a way as to

(a) minimize the possibility of injury to occupants during a collision from such causes as parts detaching from the carbody or equipment falling from the ceiling or roof

(b) minimize the loss of occupant volume resulting from structural collapse or structural penetration

(c) provide for a progressive controlled collapse of energy absorption zones of the carbody structure while limiting the average longitudinal acceleration

Structural energy absorption zones typically located at the outer ends of the carbody structure shall be activated prior to crush of other carbody structures, following the sequence and magnitude of collapse as specified in Tables 3 and 4. Tables 1 and 2 further specify required strengths for structural elements such as collision posts and corner posts, to protect passengers and operators from structural penetration and loss of occupant volume in the event of a collision with another vehicle or obstruction. Other requirements in Tables 1 and 2 specify design criteria for vehicle anticlimbing protection in vehicle-to-vehicle collisions.

Collapse shall not commence until the end sill compression load identified in Item 2 of Tables 1 and 2 has been exceeded. The end sill compression is the minimum allowable value for the initiation of crushing, with the exception of the energy absorption in Zone 1. The design end sill compression load shall be selected based on the CEM and collision survivability plan per section 8.

The performance of the energy absorption zones shall be validated through the collision scenarios specified in Tables 3 and 4. An LRV carbody shall be designed with three sequential energy absorption zones, and a streetcar carbody designed with two. Vehicles shall have geometric compatibility to enable performance of the designed crush and energy absorption mechanisms. The structural energy absorption zones shall function in sequence (i.e., the initial impact energy shall be fully absorbed by Zone 1 prior to the absorption of impact energy by Zone 2).

– *Zone 1.* The first zone is designed to absorb impact energy in the event of a relatively low-severity frontal collision with another LRV or streetcar. This energy absorption zone can be designed with a replaceable or recoverable element.

– *Zone 2.* Having consumed the energy in Zone 1, this zone is intended to accommodate collisions between two single like LRVs or streetcars with a closing speed up to 24 km/h (15 mph). Crush shall be limited to the vehicle cab section. There shall be no loss of survivable volume in the passenger and operator compartments. Proper functioning of this zone requires that the anticlimbers in both LRVs or streetcars engage to prevent override or telescoping of the vehicles.

– *Zone 3 (Applicable to Light Rail Vehicles Only).* Having consumed the energy in Zones 1 and 2, this zone is intended for higher-speed collisions to absorb the additional energy associated with collisions between two single like LRVs at a closing speed up to 40 km/h (25 mph). The crush damage in this zone shall be limited to the front cab sections of both colliding vehicles. Inelastic deformations in the passenger compartment are allowable only if a survival volume is maintained.

After all the energy absorption capability in the three zones has been exhausted in a collision, the crush behavior of the vehicle shall continue to occur in a controlled manner progressing from the cab end in a rearward direction.

The operator's cab door and seat shall be designed to allow quick emergency egress of the operator into the passenger compartment. Armrests on the operator's seat shall fold back or be easily movable to permit easy egress, and the cab-to-passenger compartment door shall open outward from the cab.

5 DESIGN LOADS AND ASSESSMENT CRITERIA (15)

This section defines load requirements used to assess the structural design of light rail and streetcar vehicle carbodies, with respect to safety of the occupants. Tables 1 and 2 contain the loading conditions and assessment criteria. Table 1 contains the requirements to assess passenger safety for light rail vehicles based upon structural loading cases. Table 2 contains the requirements to assess passenger safety for streetcars based upon structural loading cases. The structure of the carbody shall be completely assembled with the loads of all equipment included before the specified loads are applied. Each specified load or force shall be applied over the minimum area necessary to prevent local yielding or buckling with its center of action at the location specified. Where no permanent deformation is specified, localized plastic deformation is permitted, provided it is shown by analysis and/or test that it has no effect on the structural integrity of the complete carbody.

Tables 1 and 2 do not contain all loads necessary to ensure the structural integrity of a carbody. Additional loads should be considered. Maintenance loads should have generous safety margins and should consider the safety of the maintenance and operation personnel. Specification of operational loads should consider a generally accepted fatigue method and criteria, such as

AWS D1.1/D1.1M, to assess repeated loading from propulsion, braking, and track features. Infrequent exceptional loads such as rerailing recovery and emergency braking should be assessed to ensure damage does not result from their application.

6 COUPLER SYSTEM

(15) 6.1 Characteristics

The coupler system shall respond to normal and overload conditions in a predictable manner. The coupler system shall be capable of absorbing the compression and tension forces encountered in normal vehicle operation in a train, including coupling and uncoupling, without damage.

The coupler system shall also be designed with a release mechanism to respond to compressive overload conditions. The coupler system may also include a regenerative or nonregenerative energy absorption unit(s). In a collision, the draft gear elements and/or energy absorption unit(s) shall compress, followed by activation of the release mechanism, which shall allow the coupler system to retract a sufficient distance to permit the carbody anticlimbers to engage. If the collision energy is sufficiently high such that compression continues following the full retraction of the coupler system, the coupler system shall not impede the CEM response of the carbody to overload conditions. The value of the release load shall satisfy the specific characteristics of the subject transit system's intended operation. The coupler system, after activation of nonregenerative energy-absorbing mechanism(s), shall be capable of withstanding the tension loads encountered when towing. The coupler system shall at all times be vertically supported in a safe manner to prevent the coupler from falling onto the track.

(15) 7 MATERIAL

Minimum material property values as defined by a material specification or standard stated in paras. 7.1 through 7.5 or equivalent, shall be utilized.

7.1 Austenitic Stainless Steel

Structural use of austenitic stainless steel shall be in accordance with APTA PR-CS-S-004-98, Rev. 1.

7.2 Low Alloy High Tensile Steel

Structural use of low alloy high tensile (LAHT) steel shall be in accordance with the requirements of APTA PR-CS-S-034-99, Rev. 2, Section 4.2.

7.3 Aluminum

Structural use of aluminum and aluminum alloys shall be in compliance with APTA PR-CS-S-015-99.

7.4 Static Strength

The limiting static material properties shall be as given in the referenced material standard. When other standards are used, equivalency shall be demonstrated between these standards and the referenced material standards.

7.5 Nonmetallic Materials

If nonmetallic materials are utilized, then this Standard shall be applied to the extent possible. Data from internationally accepted standards that represent the performance of the material may be applied pending demonstration of equivalency to a U.S. code or standard.

8 CRASH ENERGY MANAGEMENT (CEM) (15)

To improve crashworthiness, this Standard requires that the principles of crash energy management (CEM) be applied, including the use of analytical tools and/or testing to verify that the carbody design is stable and crushes as intended. Analysis for the purpose of evaluation of load cases specified in para. 4.6 and Tables 3 and 4 shall be of the time-dependent, large-deflection type. Validation of the crush behavior by test shall be performed only if specified.

The carbody shall be designed to crush and absorb energy in a controlled manner when subjected to end loads that exceed its static load capability. The design shall be based on the CEM structural energy absorption zones per the scenarios specified in Table 3 or Table 4. A CEM and collision survivability strategy shall be developed that is compliant with the criteria provided in section 4. The strategy shall define the specific features of the carbody that will provide the required zones of energy absorption.

9 ANALYSIS

Structural analysis of the carbody and of supports for equipment weighing over 11.3 kg (25 lb) shall be performed. For any portion of the proposed design that is based on service-proven vehicle data from previous tests, historical data from operations or structural analyses as required to satisfy the corresponding portion of these requirements shall be provided.

9.1 Structural Sketch (15)

A structural sketch shall be provided in order to clearly define the primary carbody structure. The structural sketch shall include a side view, a top view showing one longitudinal half of the roof and one longitudinal half of the underframe, and typical carbody cross sections. Cross sections of the structural members, showing the shape, dimensions, material, and thickness of each member, shall be included. The members and the connections shown shall include, to the extent used in the particular design, the typical side frame and door frame posts; end, side, draft, and center sills; belt, top, and roof rails; collision and corner posts; bolsters, floor beams, and cross bearers; roof carlines and purlins; roof sheathing or corrugation; and side-frame sheathing and/or corrugation.

(15) 9.2 Linear-Elastic Stress Analysis

The carbody stress analysis shall consist of a linear-elastic finite element analysis (FEA) based upon the structural sketch and using a recognized computer FEA code, supplemented as appropriate by analytical (non-computational) stress analyses.

The results of the linear stress analysis shall include calculated stresses, allowable stresses, and margins of safety for all structural elements at all design loading conditions required by this Standard. For all linear-elastic load cases, the elastic stability of plates, webs, and flanges shall be calculated for members subject to compression and shear.

The purpose of the manual analysis shall be to examine details of the carbody (such as weld connections, welded and/or bolted joints, fatigue conditions, and column and plate stability) that are not readily handled in the FEA. The format and content of the manual analyses shall include the following as a minimum:

(a) title

(b) sketch of the item to be analyzed, with dimensions, applied forces, and other boundary conditions

(c) drawing references

(d) material properties

(e) allowable stress

(f) detailed stress analyses

(g) conclusions

(15) 9.3 Crashworthiness Analysis

The crashworthiness analysis shall be performed using a nonlinear, large-deformation explicit, time-dependent, finite element software program. Lumped mass features may be used in the finite element model to represent vehicle structure and mass located away from the crush zone and the adjacent passenger area.

The crashworthiness analysis simulation shall be of a moving train colliding into a stopped train, using the vehicle initial velocity identified in Tables 3 and 4. Both trains shall be at a ready-to-run load condition with brakes applied at the full service rate. Both trains shall be of similar design and consist of the maximum number of cars used in operation. The simulation shall be initiated with sufficient time prior to impact to allow gravitational and braking loads to develop. The collision shall occur on level tangent track. The coupler and/or end covers shall be configured in a typical service condition. Additional simulations may be required based on interoperability requirements of section 3.

The results of the simulation shall demonstrate the following:

(a) The vehicle interactions do not override or exhibit telescoping responses.

(b) Progressive structural crush begins at the end of the vehicle.

(c) Average vehicle deceleration is as defined in Tables 3 and 4.

(d) All vehicles remain upright and in line during and after the collision.

(e) Trucks remain attached to the vehicles.

(f) Global vehicle shortening is no more than 1% over any 4.57 m (15 ft) of the occupied volume (not including the operating compartment). Highly localized plastic deformation of the occupied volume not affecting the ability of the structure to meet the requirements of this Standard shall be allowed. The 4.57 m (15 ft) of the occupied volume length located at the end of the vehicle closest to the point of collision may reduce in length up to 2%.

(g) Applicable for Collision Scenario 2 of Tables 3 and 4

(1) The operating compartment seat has a minimum of 305 mm (12 in.) of survival space from the forward profile of the seat, where there is no intrusion by design, and a clear path from the seat to exit the operating compartment.

(2) Operator control consoles, walls, bulkheads, or side structures normally designed to be within the 305-mm (12-in.) space around the seat do not further intrude more than 51 mm (2 in.) toward the operator seat after the collision from the existing design position.

(h) The vertical (floor-to-ceiling) height of the operating compartment is not reduced by more than 20% after the collision. The operator must have a clear exit path through the operator's compartment and through an operator's compartment door or doorway exit. The operator's compartment doors used for exiting the operator's compartment must remain fully operable.

(i) The relative difference in elevation between the underframes of the colliding and connected vehicles does not change by more than 102 mm (4 in.).

(j) The tread of any wheel of the vehicles does not rise more than 102 mm (4 in.) above the top of rail.

(k) Maximum crush displacement of either colliding vehicle does not differ more than 25% from the average maximum crush displacement of both vehicles.

(l) There is no loss of survivable volume in the passenger compartment.

(m) Some local plastic deformation is allowed; however, deformation in the door-operating areas shall not infringe on the escape operation of the side door panels.

The simulation results shall be provided in various forms, including video animation, static displays of video frames, graphs of force deflection versus time, graphs of vehicle acceleration versus time, and energy balance data. The video animation and graphical documentation of results shall demonstrate progressive crush response and the ability of the structure to maintain survivable space required for operator and passengers. The force deflection curves shall show the crush response of the front end structure, where force is measured at the interface between the cab end structure and the passenger compartment. The acceleration history for each vehicle of the consist shall be determined by a method that computes the global vehicle acceleration. Energy data shall be included to demonstrate conservation of momentum, conservation of energy balance, and minimization of computational energy loss such as might be caused by computational element deformation (commonly referred to as hourglass energy).

10 TESTS

10.1 Objectives

Certain proof-of-design tests shall be performed in order to demonstrate the strength and stability required by this Standard. It is not necessary to carry out all tests if there are appropriate verification data in existence from previous tests on a similar structure, and correlation between the test and calculation has been established. Tests shall be carried out to verify any significant changes to the design or to the performance requirements. There is no need to repeat the tests if the production location is later changed, provided that there is no significant change in the design or manufacturing process of the carbody.

The specific objectives of the tests are to verify the strength of the carbody and, if used, the articulation system when subjected to the specified loads, to verify that no permanent deformation is present after removal of specified loads, and to validate analytic models and determine the accuracy of the analyses for load cases not tested. The test program shall comprise, as appropriate, the static simulation of selected design cases, measurements of actual stresses with electric resistance strain gauges or other suitable techniques, and measurement of the structural deformation under loads.

(15) 10.2 General

One of the first carbodies produced shall be tested to verify compliance of the design of the carbody with this Standard. The carbody shall be structurally complete, including flooring if used as part of the primary carbody structure, but shall exclude nonstructural items such as exterior and interior trim, windows, doors, seats, lights, insulation, interior lining, or any other materials that will obscure any structural member of the carbody from view. Underfloor, roof-mounted, and ceiling-mounted apparatus shall be installed or equivalent weights distributed at their respective locations. If weights are used, attachment fasteners shall duplicate the proposed designs.

For any portion of the design that is based on a service-proven vehicle, data from previous tests to satisfy the corresponding portion of these requirements may be provided.

The test procedure should include, as a minimum, the drawings, sketches, tables, and other descriptions that provide a description of the test load equipment, the location of each point at which a load or reaction is applied to the specimen, a table showing the load applied at each load point for each test increment, and the location of each load, strain, and deflection-measuring device. The force of the testing machine shall be measured by a load cell or equivalent device that is independent of the equipment producing the applied force.

10.3 Proof Load Tests

10.3.1 Test Procedures. Tests shall be conducted on a bare carbody, following its manufacture, that has been ballasted or otherwise loaded with properly distributed weight such that the carbody's weight is equivalent to that of a fully assembled ready-to-run vehicle. The tests shall be carried out in a test fixture that allows for the application of reaction forces at the points where they would occur during operation. All test measurement devices shall be verified to be within calibration. The carbody and applicable articulation system shall be equipped with strain-measuring devices in locations that will allow estimation of maximum stresses predicted by the stress analysis, in areas of stress concentration factors as determined by the stress analysis or finite element analysis. Testing shall be capable of addressing the following conditions and measurement points: (15)

(a) the strain at critical points, including window and door corners, side sill, corner and collision posts, structural shelf, and other areas

(b) deflection of carbody

(c) diagonal dimensions at window and door openings

(d) residual deflection of carbody

(e) residual strain, if any

The carbody shall be preloaded before the load tests as agreed to between the customer and the manufacturer, to stabilize the overall structure, and the maximum force shall then be applied incrementally at least twice. The customer shall approve the results of the last test. These tests shall verify that there is no permanent deformation to the carbody or individual elements when subjected to the loads identified in section 5 regarding permanent deformation.

10.3.2 Vertical Load

10.3.2.1 Test Description. The carbody, supported on trucks or a simulation thereof, shall be subjected to a vertical load test. Consideration should be given to (15) the stresses already existing due to weight of the bare carbody structure itself.

A test load equal to the vertical load specified in Item 1 of Table 1 or Table 2 shall be applied in a minimum of four evenly spaced increments. The test load may be applied by means of weights or jacks, but shall be distributed in proportion to the distribution of weight in the finished vehicle. The carbody shall be unloaded in the increments in which it was loaded, in reverse order. Strain gauge and deflection readings shall be taken at each load increment.

(15) **10.3.2.2 Test Criteria.** The test results shall verify the following:

(a) Stresses are in accordance with the requirements of section 5.

(b) Vertical deflection readings plotted against load do not vary by more than ±7.5% from a straight line, with one end point at the origin and the other at the point that represents the measured deflection for the specified section 5 load.

(c) Strain readings plotted against load do not vary by more than ±7.5% from a straight line (linear) deflection curve, with one end point at the origin (zero load) and the other at the point that represents the measured deflection for the specified section 5 load.

(d) Maximum stresses calculated from strain readings in any structural element do not exceed the allowable stresses approved prior to starting the test program as part of the stress analysis.

(e) Recorded residual vertical deflection between the carbody bolsters following removal of the specified section 5 load does not exceed 1.0 mm (0.04 in.).

(f) Recorded residual carbody transverse width and/or opening diagonal changes in dimensions following removal of the specified section 5 load do not exceed 1.0 mm (0.04 in.).

(g) Indicated residual strains at strain gauges on principal structural elements following removal of the applied loads should not exceed 5% of the yield strength divided by the elastic modulus of the material to which the strain gauge is attached. Higher residual strains may be permitted based upon further investigation (e.g., consideration of instrumentation error and boundary condition variations).

(h) There are no visual permanent deformations, fractures, cracks, or separations in the carbody. Any broken weld shall be analyzed to determine if the failure is the result of either inadequate weld quality or overstress before repair or redesign of the area, and retest.

10.3.3 Compression Loads

(15) **10.3.3.1 Test Description.** The carbody, supported on trucks or equivalent supports to allow longitudinal movement, shall be subjected to compression load tests. The carbody shall be ballasted or otherwise loaded with properly distributed weights such that its weight is equivalent to that of a fully assembled ready-to-run vehicle. Test loads equal to those specified in Items 2 through 5 of Table 1 or Table 2 shall be individually applied. The test loads shall be applied horizontally at the anticlimber on the carbody longitudinal centerline, or to the coupler anchorage as is appropriate for the test being performed. No allowance shall be made for the camber of the carbody. Cushioning by means of soft metal sheets shall be provided for uniform bearing of the applied load. The test load application equipment (e.g., hydraulic rams) shall be configured in such a manner such that the "humping" deformation behavior of the car-shell structure during the compression loading does not transfer any portion of the car-shell weight from the trucks or simulated supports to the load application equipment. It is recommended that measures be taken in the test setup to prevent binding of the loading rams in the test article as the compression load is applied. The test loads shall be applied with incremental increases, and shall include at least one return to a load not greater than 9 kN (2,025 lb) after attaining not less than 80% of the required maximum load.

10.3.3.2 Test Criteria. The test results shall verify (15)
the following:

(a) The maximum stresses calculated from the strain reading in any structural element do not exceed the corresponding allowable stresses as specified in section 5.

(b) Indicated residual strains at strain gauges on principal structural elements following removal of the applied loads do not exceed 5% of the yield strength divided by the elastic modulus of the material to which the strain gauge is attached. Higher residual strains may be permitted based upon further investigation (e.g., consideration of instrumentation error and boundary condition variations).

(c) There are no visual permanent deformations, fractures, cracks, or separations in the carbody. Any broken welds shall be analyzed to determine if the failure is the result of either inadequate weld quality or overstress before repair or redesign of the area, and retest.

10.3.4 Collision Post (Collision Wall) and Corner Post Loads

10.3.4.1 Test Description. The ability of the colli- (15)
sion posts (collision wall), corner posts, and associated supporting structures to resist the elastic design loads specified in Table 1 or Table 2 shall be tested. The placement of the applied loads shall be for the worst-case condition, or as agreed to by the customer and the manufacturer. The test loads may be applied to one end (cab) of a structurally complete carbody or, as an alternate, a separate end frame section may be constructed and tested. If the alternate method is chosen, the test element shall simulate to the maximum extent possible the location, the degree of fixity, and the magnitude and direction of reactions of the supporting carbody. Cushioning

by means of soft metal sheets shall be provided for uniform bearing. Loads that are specified in a range on either side of the longitudinal direction need only be applied in the longitudinal direction (0 deg). Loads that are specified in a range on either side of the transversal direction need only be applied in the transversal direction (90 deg).

(15) **10.3.4.2 Test Criteria.** The test results shall verify the following:

(a) The maximum stresses calculated from the strain reading in any structural element do not exceed the corresponding allowable stresses as specified in section 5.

(b) Indicated residual strains at strain gauges on the principal structural elements following removal of the applied loads do not exceed 5% of the yield strength divided by the elastic modulus of the material to which the strain gauge is attached. Higher residual strains may be permitted based upon further investigation (e.g., consideration of instrumentation error and boundary condition variations).

(c) There shall be no visual permanent deformation, fractures, cracks, or separations in the carbody. Any broken welds shall be analyzed to determine if the failure is the result of either inadequate weld quality or overstress before repair or redesign of the area, and retest.

10.4 Crash Energy Management Tests

10.4.1 Test Description. Tests to validate the CEM design, if prescribed, may include a series of tests of the individual elements, testing of subassemblies, or testing the global structure. While it is recommended as a minimum to test each crush element, the actual validation of the global crush behavior may also require intermediate steps.

The individual elements or the global structure may be tested either dynamically or quasi-statically.

10.4.2 Test Criteria. These tests serve to demonstrate compliance with the CEM requirements in section 8.

10.5 Coupling Impact Tests

These tests serve to demonstrate that the vehicle can remain fully serviceable under coupling impacts up to the coupling speed requirements of Item 4 of Table 1 or Table 2.

11 REFERENCES (15)

APTA PR-CS-S-004-98, Rev. 1, Standard for Austenitic Stainless Steel for Railroad Passenger Equipment

APTA PR-CS-S-015-99, Standard for Aluminum and Aluminum Alloys for Passenger Equipment Car Body Construction

APTA PR-CS-S-034-99, Rev. 2, Standard for the Design and Construction of Passenger Railroad Rolling Stock

Publisher: American Public Transportation Association (APTA), 1666 K Street, NW, 11th Floor, Washington, DC 20006 (www.apta.com)

AWS D1.1/D1.1M (latest edition), Structural Welding Code — Steel

AWS D1.2/D1.2M (latest edition), Structural Welding Code — Aluminum

AWS D17.2/D17.2M (latest edition), Specification for Resistance Welding for Aerospace Applications

Publisher: American Welding Society (AWS), 8669 NW 36 Street, No. 130, Miami, FL 33166 (www.aws.org)

IEEE/ASTM SI 10-1997, Standard for Use of the International System of Units (SI): The Modern Metric System

Publisher: Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Lane, Piscataway, NJ 08854 (www.ieee.org)

SAE Paper No. 1999-01-0071, NHTSA's Vehicle Compatibility Research Program

Publisher: SAE International, 400 Commonwealth Drive, Warrendale, PA 15096 (www.sae.org)

(15)

Table 1 Structural Load Requirements for LRVs

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
1	Maximum carbody vertical load	Evenly distributed car volume capacity load	Stress not to exceed 65% of the carbody structural member yield strength, and no loss of local stability
2	End sill compression	Load of 400 kN (90,000 lb) applied on the anticlimber in the longitudinal (inward) direction of the carbody	No permanent deformation of any structural member or structural sheathing, with the possible exception of the Zone 1 energy absorption area
3	Coupler anchorage compression load (see section 6)	Carbody structure shall support maximum possible load from the coupler. This load is commonly called the disconnect or release load, produced by the coupler load as defined in section 6, applied in the longitudinal (inward) direction.	No permanent deformation of any structural member or structural sheathing
4	Coupling impact	Coupling at a vehicle closing speed of 8 km/h (5 mph)	No permanent deformation of any structural member, structural sheathing, or structural connection, with the exception of the Zone 1 energy absorber
5	Coupler anchorage tensile load	Loads shall meet the required duty as specified in section 6	No permanent deformation of any structural member or structural sheathing
6	Collision post shear load (collision posts or protective collision wall structures)	Load equal to the end sill compression load, applied to each collision post separately over a surface area of the collision post in the longitudinal (inward) direction, or applied to a collision wall structure over a surface area of the wall at two separately located lateral positions at 30% of the end frame width relative to either side of vehicle longitudinal centerline *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height measured from the top of end frame	Ultimate strength of any carbody structure not to be exceeded
7	Collision post load (collision posts or protective collision wall structure)	Load of 133 kN (30,000 lb) positioned at 380 mm (15 in.) above top of underframe, applied to each collision post simultaneously over surface areas of the collision posts, or applied simultaneously to collision wall structure areas in two locations symmetrically positioned laterally at 30% of the end frame width relative to either side of vehicle longitudinal centerline *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height centered on the point of loading	No permanent deformation of any structural member, structural sheathing, or structural connection

Table 1 Structural Load Requirements for LRVs (Cont'd)

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
8	Corner post shear load	Load of 133 kN (30,000 lb) applied to each corner post (or corner structure) over a surface area of the corner post in separate longitudinal and transverse directions *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) or 15 deg on either side of transverse (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height measured from the top of end frame	Ultimate strength of any carbody structure not to be exceeded
9	Corner post loads (elastic design loads)	Load of 67 kN (15,000 lb) positioned at 380 mm (15 in.) above top of underframe, applied to each corner post (corner structure) over a surface area of the corner post in separate longitudinal (inward) and transverse (inward) directions *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) or 15 deg on either side of transverse (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height centered on the point of loading	No permanent deformation of any structural member, structural sheathing, or structural connection
10	Structural shelf	Longitudinal load of 67 kN (15,000 lb) applied at any point in the longitudinal (inward) direction *(a)* Area of load application shall not exceed 250 mm × 150 mm (10 in. × 6 in.) *(b)* Load direction variation permitted within 15 deg on either side of longitudinal (inward)	No permanent deformation of any structural member, structural sheathing, or structural connection
11	Side wall load, at side sill	Load of 178 kN (40,000 lb) applied in the transverse (inward) direction at the side sill, and distributed along an area of 2.4 m × 150 mm (96 in. × 6 in.), not including the doorways	No permanent deformation of any structural member, structural sheathing, or structural connection. Localized deformation of the side wall profile in the area of the load application is permitted.
12	Side wall load, at belt rail	Load of 44 kN (10,000 lb) applied in the transverse (inward) direction at the belt rail, and distributed along an area of 2.4 m × 150 mm (96 in. × 6 in.), not including the doorways	No more than 75 mm (3 in.) of permanent structural deformation into the vehicle interior. This load shall not result in sharp edges or protrusions in the vehicle interior.

Table 1 Structural Load Requirements for LRVs (Cont'd)

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
13	Roof, concentrated load	Load of 1 330 N (300 lb) spaced over an area of 380 mm × 330 mm (15 in. × 13 in.)	No permanent deformation of any structural member, structural sheathing, or structural connection
14	Truck-to-carbody attachment	Separately applied loads as follows: *(a)* a longitudinal load produced from the collision scenarios referenced in section 8. Alternatively, a longitudinal load equivalent to 5 times the weight of the heaviest truck applied through the center of gravity of the truck. *(b)* a load as specified in Item 11 above, with two wheels on the opposite side of the truck fixed laterally at the wheel flanges at the height of the rail. *(c)* a vertical load of 2 times the weight of the truck.	*(a)* Truck shall remain attached *(b)* Truck shall remain attached *(c)* Yield strength in the attachment mechanism shall not be exceeded
15	Equipment attachments	Separately applied acceleration loadings of ±5*g* applied in the longitudinal direction, ±2*g* applied in the transverse direction, and ±3*g* applied in the vertical direction	Not to exceed ultimate strength in the attachment mechanism

Table 2 Structural Load Requirements for Streetcars (15)

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
1	Maximum carbody vertical load	Evenly distributed car volume capacity load	Stress not to exceed 65% of the carbody structural member yield strength, and no loss of local stability
2	End sill compression	Load of 300 kN (67,500 lb) applied on the anticlimber in the longitudinal (inward) direction of the carbody	No permanent deformation of any structural member or structural sheathing, with the possible exception of the Zone 1 energy absorption area
3	Coupler anchorage compression load (see section 6)	Carbody structure shall support maximum possible load from the coupler. This load is commonly called the disconnect or release load, produced by the coupler load as defined in section 6, applied in the longitudinal (inward) direction.	No permanent deformation of any structural member or structural sheathing
4	Coupling impact	Coupling at a vehicle closing speed of 8 km/h (5 mph)	No permanent deformation of any structural member, structural sheathing, or structural connection, with the exception of Zone 1 energy absorber
5	Coupler anchorage tensile load	Loads shall meet the system duty (see section 6)	No permanent deformation of any structural member or structural sheathing
6	Collision post shear load (collision posts or protective collision wall structures)	Load equal to the end sill compression load, applied to each collision post separately over a surface area of the collision post in the longitudinal (inward) direction, or applied to a collision wall structure over a surface area of the wall at two separately located lateral positions at 30% of the end frame width relative to either side of vehicle longitudinal centerline *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height measured from the top of end frame	Ultimate strength of any carbody structure not to be exceeded
7	Collision post load (collision posts or protective collision wall structure)	Load of 100 kN (22,500 lb) positioned at 380 mm (15 in.) above top of underframe, applied to each collision post simultaneously over surface areas of the collision posts, or applied simultaneously to collision wall structure areas in two locations symmetrically positioned laterally at 30% of the end frame width relative to either side of vehicle longitudinal centerline *(a)* Load application direction variation permitted within 15 deg on either side of longitudinal (inward) *(b)* The applied load area shall not exceed 250 mm (10 in.) in width nor 150 mm (6 in.) in height centered on the point of loading	No permanent deformation of any structural member, structural sheathing, or structural connection