ASME RT-2–2014

(Revision of ASME RT-2–2008)

Safety Standard for Structural Requirements for Heavy Rail Transit Vehicles

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

Date of Issuance: March 12, 2014

The next edition of this Standard is scheduled for publication in 2019. This Standard will become effective 6 months after the Date of Issuance.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org/ as they are issued.

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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, functional, performance, and operability requirements, as well as mechanical systems, components, and structural requirements for rail transit vehicles. Rail transit (RT) includes conventional subway (rapid) transit rail vehicles and light rail vehicles and excludes freight, commuter, high-speed, or any other rail vehicles 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 the Committee's consideration of factors such as technological advances, new data, and changing environmental and industry needs.

Both SI 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 the "Standard for Use of the International System of Units (SI): The Modern Metric System," IEEE/ASTM SI 10-1997, or latest revision.

The Standards Committee will review and address all comments, suggestions, and recommendations intended to improve this Standard, especially when the comments are based on actual experience in its application. Suggestions for changes to this Standard should be submitted to the Secretary of the RT Committee, The American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990, and should be in accordance with the following format:

(a) Cite the specific paragraph designation of the pertinent volume.

(b) Indicate the suggested change (addition, deletion, or revision).

(c) Briefly state the reason and/or evidence for the suggested change.

(d) Submit suggested changes for more than one paragraph in the order that the paragraphs appear in the volume.

Safety codes and standards are intended to enhance public safety. Revisions result from committee consideration of factors such as technological advances, new data, and changing environmental and industry needs. Revisions do not imply that previous editions were inadequate.

The first edition of RT-2 was ANSI approved in 2008. This edition contains revisions throughout the document. It was approved by the RT Standards Committee and by ASME, and was approved by the American National Standards Institute on January 28, 2014.

ASME RT COMMITTEE
Rail Transit Vehicle Standards

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

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CORRESPONDENCE WITH THE RT COMMITTEE

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 revision, 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

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, which 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 that are open to the public. Persons wishing to attend any meeting should contact the Secretary of the RT Standards Committee.

INTRODUCTION

(14)

Safety of heavy rail transit operations is a system characteristic. As do all transportation options in a given corridor, this operation has certain risks, including derailment and collision with another vehicle. The risks are mitigated by the design of the signal system, and other systems 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 vehicle 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 for the design of the carbody of heavy rail transit vehicles. It also considers recent developments in the design of rail carbody structures intended to optimize the structure performance under the conditions of an overload, such as might occur during a collision. This topic 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 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. This Standard requires the incorporation of CEM principles in the design of heavy rail transit vehicles. For multiple unit operation, distributing structural energy absorption through the train has been shown to be beneficial.

ASME RT-2–2014
SUMMARY OF CHANGES

Following approval by the ASME RT Committee and ASME, and after public review, ASME RT-2–2014 was approved by the American National Standards Institute on January 28, 2014.

ASME RT-2–2014 includes editorial changes, revisions, and corrections identified by a margin note, **(14)**.

Page	*Location*	*Change*
vii	Introduction	Revised
1	Section 1	Revised
	Section 2	(1) Definitions of *carbody (heavy rail)* and *vehicle vertical loads* revised (2) Definition of *light rail vehicles* deleted (3) Definition of *yield strength* added
2	Section 3	First paragraph revised
3, 4	Table 1	(1) Items 1, 8, 17, and 18 revised (2) Items 19 through 21 deleted
5	4.4	Third sentence revised
	5.1	Last paragraph revised
	Section 6	Revised
6	Section 8	Revised
7–9	Table 2	Added
	9.3	Revised in its entirety
	10.3.1	First sentence revised
	10.3.2	Revised
	10.3.3.1	Revised

SAFETY STANDARD FOR STRUCTURAL REQUIREMENTS FOR HEAVY RAIL TRANSIT VEHICLES

(14) 1 SCOPE

1.1 Subjects Covered by This Standard

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

1.2 Subjects Not Addressed by This Standard

There are several issues related to safety 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

1.3 Effective Date

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

(14) 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 the anticlimber of an opposing or otherwise coupled vehicle to resist relative vertical travel between the two carbodies during a collision.

antitelescoping plate: a single structural member that spans the full width of the carbody at the top of the end frame, that is attached to the tops of the collision and corner posts, and is designed to transmit the collision and corner post top reaction loads to the carbody sides.

belt rail: a longitudinal structural member in the side frame arranged below the passenger side windows.

carbody (heavy rail): the heavy rail vehicle body consists of the main load-carrying structure above all truck suspension units. It includes all components 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.

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

collision posts (heavy rail transit): a set of two structural posts located at each end of the carbody, extending from the bottom of the underframe structure up to an antitelescoping plate. 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.

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

corner posts (RT-2): a set of two structural posts located at the outside corners of the passenger compartment or at the extreme corners of the carbody, extending from the bottom of the underframe structure up to an antitelescoping plate and to the roof at the top of the side frame at its intersection with the roof.

crash energy management (CEM): a method of design and manufacture of vehicle structures that assigns certain sections of the carbody the task of absorbing a portion of the energy of collision 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. The use of supplementary energy-absorbing element(s) may be specified.

crashworthiness (RT-2): the ability of a carbody to manage the energy of a collision while maintaining structural integrity, so as to minimize injury to occupants.

end frame (RT-2): at the coupler ends, the end frame consists of structure inboard of and supporting the anticlimber, corner posts at the juncture of the front end and side frames, collision posts located at the approximate one-third points of the end frame width, the end structural shelf or transverse beam, and sheathing connected to the structural framing members.

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

heavy rail transit vehicle: a typically electrically propelled, bidirectional vehicle, capable of multiple unit operation, and designed for rapid, high-level boarding and discharging of passengers. The vehicle is operated on a mode of rail rapid transit generally characterized by fully grade-separated construction on exclusive rights of way, with station platforms at the floor level of the vehicles. These systems are commonly referred to as subways or metros.

permanent deformation:

(a) for design, 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.

(b) for testing, a condition resulting from a stress greater than the 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.

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 its stress analysis.

structural shelf (heavy rail transit): a horizontal structural member installed at the cab end of the vehicle, located between the collision post and the corner post on each side, at a height equivalent to the bottom of the windshield.

telescoping (RT-2): 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 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 published by 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.

3 INTEROPERABILITY (14)

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 heavy rail transit vehicle shall incorporate an anticlimber at each end of the vehicle. The height and design of the anticlimber and coupler on new heavy rail transit vehicles shall be compatible with existing heavy rail transit vehicles that are operated on the same routes of the subject transit system. The anticlimber shall be designed for engagement between all vehicle types to mitigate telescoping in a collision, including any condition of failed or deflated suspension elements. The coupler system shall be of a "shearback" design, to permit the couplers to collapse during a collision so as to allow engagement of the anticlimbers. See section 6 for additional requirements.

3.2 Multiple Unit Operation

All combinations of vehicles to be operated within a train shall be considered in assessing the effect of multiple unit operation in a collision.

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 strength of connections between structural members of the end frame for Items 6 through 11 in Table 1 shall exceed the ultimate load-carrying capacity of the

Table 1 Structural Load Requirements (14)

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
1	Maximum carbody weight	Evenly distributed car volume capacity, load not including trucks	Stress not to exceed 65% of the yield strength
2	End sill compression	A minimum load of 890 kN (200,000 lb), applied in the longitudinal inward direction on the anticlimber	No permanent deformation of any structural member or structural sheathing
3	Coupler anchorage compression load (see section 6)	Load of 110% of the maximum possible load (commonly called the disconnect or release load) produced by the coupler load, as defined in section 6 applied in 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 or structural sheathing not including the anticlimber
5	Coupler anchorage tensile load	Loads shall meet the subject transit system duty (see section 6)	No permanent deformation of any structural member or structural sheathing
6	Collision post shear load	Load equal to the end sill compression load, applied in the longitudinal inward direction to each post separately at the top of the underframe	No permanent deformation of any structural member, structural sheathing, or structural connections
7	Collision post load (elastic design load)	Loads equal to 33% of the end sill load applied to each post, with both posts loaded simultaneously up to 15 deg on either side of the longitudinal inward direction 450 mm (17.75 in.) above the top of the underframe	No permanent deformation of any structural member, structural sheathing, or structural connections
8	Collision post load (elastic–plastic design load)	Loads applied per the elastic design load case (see Item 7 above applied to a single post) beyond the elastic design load, until the center of the post has deflected at least one-third of its full depth measured at the middle of the post from a line connected between the top and bottom of the post when initially unloaded	The load shall remain above the elastic design load. There shall be no complete separation of the posts, its connection to the underframe, and its connection to either the roof structure or at the antitelescoping plate.
9	Corner post loads	Two loads, applied separately, to one post at the top of the underframe, one load equal to 25% of the end sill compression load applied in the longitudinal inward direction, and a second load equal to 25% of the end sill compression load applied in the transverse inward direction	No permanent deformation of any structural member, structural sheathing, or structural connections
10	(a) Corner post loads (elastic design load)	Two loads, applied separately, to one post 450 mm (17.75 in.) above the top of the underframe, one load equal to 12% of the end sill compression load applied in the longitudinal inward direction, and a second load equal to 6% of the end sill compression load applied in the transverse inward direction	No permanent deformation of any structural member, structural sheathing, or structural connections

(14)

Table 1 Structural Load Requirements (Cont'd)

Item	Type of Load	Specified Load on Carbody	Acceptance Criteria
10	(b) Corner post loads (elastic-plastic design load)	Loads applied per the elastic design load case [see Item 10(a) above] beyond the elastic design load, until the center of the post has deflected at least one-third of its full depth measured at the middle of the post from a line connected between the top and bottom of the post when initially unloaded	The load shall remain above the elastic design load. The connections between the corner post and all other structural members have not separated.
11	Structural shelf	Load equal to 7.5% of the end sill compression load at any point in the longitudinal inward direction	No permanent deformation of any structural member or structural sheathing
12	Anticlimber	Load equal to the end sill compression load applied at the vehicle centerline in the longitudinal inward direction, in combination with separately applied vertical (upward and downward) load (with one less rib than total) of 334 kN (75,000 lb)	No permanent deformation of any structural member or structural sheathing. Some localized deformation of the anticlimber is permitted.
13	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.) including the doorways	No permanent deformation of any structural member or structural sheathing. Some localized deformation of the side wall profile in the area of the load application is permitted.
14	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.
15	Roof, in rollover condition	Vehicle shall be able to rest upon its roof	Structural damage in occupied areas limited to roof sheathing and roof framing members
16	Roof, concentrated load	Load of 1 330 N (300 lb) spaced over an area of 380 mm × 330 mm (15 in. × 13 in.) Separately applied loads	No permanent deformation of any structural member or structural sheathing
17	Truck to carbody attachment	(a) 667 kN (150,000 lb) applied anywhere on the truck in the horizontal plane through the center of truck rotation (b) A vertical load of two times the weight of the heaviest truck	(a) Not to exceed ultimate strength in the attachment mechanism (b) Not to exceed yield strength in the attachment mechanism
18	Equipment attachments	Separately applied loadings of ±5g applied in the longitudinal direction, ±2g applied in the transverse direction, and ±3g applied in the vertical direction	Not to exceed ultimate strength in the attachment mechanism

weakest member joined. For these load cases, the ultimate load-carrying capacity is established by applying the load at the location and in the direction specified in Table 1 but increased in magnitude to the maximum load that can be resisted by the structure, as determined by observing that further increase in deflections will result in a decrease in the load capable of being carried by the structure. References to sheathing in Table 1 refer only to structurally related (load carrying) sheathing.

4.1 Welding

Design of welded structures shall be in accordance with AWS D15.1, AWS D1.1 for steel, and AWS D1.2 for aluminum.

4.2 Design Parameter Tolerance

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.

4.3 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.

(14) 4.4 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 trucks shall remain attached to the carbody when the vehicle is raised unless first intentionally detached. The ultimate strength of the attachment mechanism in the horizontal plane (ultimate horizontal strength) 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.

5 DESIGN LOAD REQUIREMENTS

This section defines load requirements to be used for the design of heavy rail transit vehicles, including static loads representing normal and exceptional conditions. The structure of the carbody shall be completely assembled with the loads of all equipment included before the specified loads are applied. Each specified force shall be applied over the minimum area necessary to limit local yielding or buckling, with its center of action at the location specified. In Table 1, where no permanent deformation is required, localized plastic deformation is permitted, provided it has no effect on the structural integrity of the complete carbody.

5.1 Crashworthiness (14)

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 the detachment of parts of the carbody or falling equipment mounted in the ceiling or on the 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

Structural energy absorption zones shall be located at the ends of the carbody structure and shall be activated prior to crush of other carbody structures, following the sequence and magnitude of collapse as specified in Table 1 and para. 9.3. Table 1 further specifies 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 Table 1 specify design criteria for vehicle anticlimbing protection in vehicle-to-vehicle collisions, and carbody roll-over strength. section 10 describes the analytical and test principles used to verify the requirements in Table 1 that are met.

5.2 Jacking and Hoisting Loads

The loading conditions and the margins of safety of stresses below yield strength shall be specified (see Table 1).

6 COUPLER SYSTEM (14)

The design of the coupler system, including drawbars, draft gear, and attachments to the carbody, 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 be designed with a release mechanism to respond to compressive overload conditions. The coupler system may also include a recoverable or nonrecoverable 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 forces are 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 intended operation. The coupler system, after activation of the primary (first shear mechanism) compression overload, shall be capable of absorbing the tension forces encountered when towing. The coupler system at all times shall be supported in a safe manner.

7 MATERIALS

Minimum material property values as defined by a material specification or standard shall be utilized.

7.1 Austenitic Stainless Steel

Structural use of austenitic stainless steel shall be in accordance with American Public Transportation Association Safety Standard SS-C&S-004-98, Standard for Austenitic Stainless Steel for Railroad Passenger Equipment, or equivalent.

7.2 Low Alloy High Tensile Steel

Structural use of low alloy high tensile (LAHT) steel shall be in accordance with the requirements of para. 4.2 of American Public Transportation Association Safety Standard SS-C&S-034-99, Standard for the Design and Construction of Passenger Railroad Rolling Stock, or equivalent.

7.3 Aluminum

Structural use of aluminum and aluminum alloys shall be in compliance with American Public Transportation Association Safety Standard SS-C&S-015-99, Standard for Aluminum and Aluminum Alloys for Passenger Equipment Carbody Construction, or equivalent.

7.4 Static Strength

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

7.5 Nonmetallic

If nonmetallic materials are being 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.

(14) 8 CRASH ENERGY MANAGEMENT (CEM)

To improve crashworthiness, this Standard requires that the analytic and test principles of Crash Energy Management (CEM) be applied, including the use of analytical tools to verify that the carbody design is stable during crushing as intended. Analysis for the purpose of evaluation of the load cases specified in Table 2 shall be of the time-dependent, large deflection type. Validation of the crush behavior by test shall be performed only if specified.

A CEM and collision survivability strategy shall be developed that is compliant with the criteria provided in section 5, para. 9.3, and other specified requirements. 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 strategy shall define the specific features of the carbody that will provide the required zones of energy absorption. The design shall be based on the requirements of Table 2.

NOTE: The specifications given within this Standard for CEM represent a basis for protecting passengers when vehicles are involved in collisions. The specifications do not address all the considerations that may need to be examined in light of vehicle design and operating variances. For example, users of this Standard may need to conduct further crashworthiness analyses that address a variety of factors including collisions with incompatible vehicle equipment strength or geometry, or conditions of the coupler engagement during collisions.

9 ANALYSIS

Structural analysis of the carbody, and of supports for equipment weighing over 30 kg (66 lb), shall be performed.

For any portion of the proposed design which is based on a 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

A structural sketch where specified shall be provided to define the primary carbody structure in advance of formal stress analysis and structural drawings. 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; anti-telescoping plate; bolsters, floor beams, and cross bearers; roof carlines and purlins; roof sheathing or corrugation; and side frame sheathing and/or corrugation.

9.2 Linear Elastic Stress Analysis

The carbody stress analysis, based upon the structural sketch, shall consist of a linear-elastic Finite Element Analysis (FEA) using a recognized computer FEA code, supplemented by a manual stress analysis.

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.

Table 2 Crashworthiness (14)

Type of Load	Specified Load on Carbody	Acceptance Criteria
Scenario 1	Two ready-to-run trains, one traveling at 24 km/h (15 mph) into a stopped train, brakes applied on both trains at full-service rate, per scenario in para. 9.3.	Preserve occupied volume for passengers and preserve survival space in operating cab, per para. 9.3.
Scenario 2	Two ready-to-run trains, one traveling at 40 km/h (25 mph) into a stopped train, brakes applied on both trains at full-service rate, per scenario in para. 9.3.	Preserve occupied volume for passengers, per para. 9.3.

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

(14) **9.3 Crashworthiness Analysis**

The crashworthiness analysis shall be performed using a nonlinear large deformation explicit finite element software program such as LS-DYNA, ABAQUS, or equal. 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 simulations shall be a moving train colliding into a stopped train, using the vehicle load condition, initial velocity, and brake application status identified in Table 2. 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 exhibit overriding or telescoping responses.

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

(c) Average vehicle deceleration shall be 7.5*g* or less.

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

(e) Trucks must remain attached to the vehicles.

(f) Global vehicle shortening shall be no more than 1% over any 4.6 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 4.6 m (15 ft) of the occupied volume length located at the end of the vehicle may reduce in length up to 2%.

(g) The operating compartment seat shall have a minimum of 30.5 cm (12 in.) of survival space from the edges of the seat where there is no intrusion, and a clear path from the seat to exit the operating compartment after the collision.

(h) The vertical (floor to ceiling) height of the operating compartment shall not be reduced by more than 20% after the collision.

(i) The relative difference in elevation between the underframes of the colliding and connected vehicles shall not change by more than 101.6 mm (4 in.)

(j) The tread of any wheel of the vehicles shall not rise more than 101.6 mm (4 in.) above the top of rail.

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 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.

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 such items 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, 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 which provide a description of the test load equipment, the location of each point that 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 shall be ballasted or otherwise loaded with properly distributed weights equivalent to the weight 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. The carbody shall be equipped with strain measuring devices in locations which 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. The following shall be measured during tests: **(14)**

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

(b) deflection

(c) diagonal dimensions at window and door openings

(d) residual deflection, if any

(e) residual strain, if any

The carbody shall be preloaded before the load tests to stabilize the overall structure, and the maximum force shall then be applied incrementally at least twice. These tests shall verify that there is no permanent deformation to the carbody or individual elements when subjected to the following loads, identified in section 5.

10.3.2 Vertical Load **(14)**

10.3.2.1 Test Description. The carbody, supported on trucks or a simulation, shall be subjected to a vertical load test. To account for the stresses already existing due to weight of the bare carbody structure itself, a test load is to be applied in two steps.

Step 1: A uniformly distributed test load equivalent to the bare carbody structure weight is to be applied with both strain gauge and deflection readings taken.

Step 2: A test load equal to the maximum carbody weight specified in Table 1, Item 1 minus the bare carbody structure weight shall be applied in a minimum of four increments with similar values recorded as in Step 1.

The resultant combined Step 1 and Step 2 stress values (obtained from corresponding strain gauges) as well as combined deflection values are to meet the test criteria as defined in para. 10.3.2.2 below. 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 that it was loaded, in reverse order. Strain gauge and deflection readings shall be taken at each load increment.

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 applied 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 applied 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 which represents the measured strain 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 specified section 5 load do not exceed 60 microstrain including instrumentation error.

(h) Carbody deflection, as measured during the vertical load tests under a car volume capacity load, shall not be more than the design camber in the side sill at any point between the carbody bolsters.

(i) 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 from overstress before repair or redesign of the area, and retested.

10.3.3 Compression Loads

(14) **10.3.3.1 Test Description.** The carbody, supported on trucks or a simulation to allow longitudinal movement, shall be subjected to compression load tests. The carbody shall be ballasted or otherwise loaded with properly distributed weights equivalent to the weight of a fully assembled ready-to-run vehicle. Test loads equal to those specified in Table 1, Items 2, 3, and 4 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 to assure uniform bearing of the applied load. The test load application equipment (e.g., hydraulic rams) shall be configured in such a manner 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 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 maximum load do not exceed 60 microstrain including instrumentation error.

(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 from overstress before repair or redesign of the area, and retested.

10.3.4 Collision Post and Corner Post Loads: Elastic Design Loads

10.3.4.1 Test Description. The ability of the collision posts, corner posts, and associated supporting structures to resist the elastic design loads specified in Table 1 shall be tested. The placement of the applied loads shall be for the worst-case condition. 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 magnitude and direction of reactions of the supporting carbody. Cushioning by means of soft metal sheets shall be provided to assure uniform bearing of the applied load. Loads which are specified in a range on either side of the longitudinal direction need only be applied in the longitudinal direction (0 deg).

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 maximum load do not exceed 60 microstrain including instrumentation error.

(c) There shall be 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 from overstress before repair or redesign of the area, and retested.

10.3.5 Collision Post Loads: Elastic–Plastic Design Loads

10.3.5.1 Test Description. The ability of the collision posts and associated supporting structural members to resist the elastic-plastic design load specified in Table 1, Item 8 shall also be tested, in order to demonstrate the ductility of the collision posts. The placement of the applied load shall be as specified in Table 1, Item 8. It is recommended that the test loads be applied to a special test article consisting of an end frame and sufficient carbody to provide a representative support condition. Cushioning by means of soft metal sheets shall be provided to assure uniform bearing of the applied load.

10.3.5.2 Test Criteria. The test results shall verify the following:

(a) The load remains above the elastic design load.

(b) The connections between the collision post and all other structural members have not separated.

(c) The post has deflected a minimum of one-third of its depth.

10.4 Crash Energy Management Tests

10.4.1 Test Description. Tests to validate the CEM design 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.

Element energy tests shall be performed on each element type to validate its design. While it is recommended that full-size elements be used during the testing, reduced scale replicas may be used.

Testing of the individual elements or the global structure may be done either dynamically or quasi-statically.

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

10.5 Coupling Impact Tests

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

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