

ACI 544.7R-16

Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

Reported by ACI Committee 544

Emerging Technology Series



American Concrete Institute

Always advancing



Documents

Document Sharing Hub



Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

Reported by ACI Committee 544

Barzin Mobasher, Chair
Neven Krstulovic-Opara, Secretary

Clifford N. MacDonald, Membership Secretary

Corina-Maria Aldea
Emmanuel K. Attiogbe
Mehdi Bakhshi*
Nemkumar Banthia
Joaquim Oliveira Barros
Amir Bonakdar
Amanda C. Bordelon
Jean-Philippe Charron
Xavier Destree
Ashish Dubey
Mahmut Ekenel
Liberato Ferrara
Gregor D. Fischer
Dean P. Forgeron
Emilio Garcia Taengua

Rishi Gupta
Heidi Helmink
George C. Hoff
Marco Invernizzi
John Jones
David A. Lange
Maria Lopez de Murphy
Michael Mahoney
Bruno Massicotte
James Milligan
Nicholas C. Mitchell Jr.
Vera Nasri†
Jeffrey L. Novak
Giovanni A. Plizzari†
Klaus Alexander Rieder

Pierre Rossi
Steve Schaeff
Surendra P. Shah
Flavio de Andrade Silva
Giuseppe Tiberti†
Thomas E. West
Kay Wille
Robert C. Zellers

James I. Daniel
Sidney Freedman
Christian Meyer
Henry J. Molloy‡
Antoine E. Naaman
Venkataswamy Ramakrishnan

*Chair of the task group that prepared this report.

†Individuals who prepared this report.

‡Deceased.

Consulting Members

P.N. Balaguru
Hiram Price Ball Jr.
Gordon B. Batson
Arnon Bentur
Andrzej M. Brandt

V. Nasri is acknowledged as a significant contributor to this report. Special acknowledgements to M. Invernizzi, W. Bergeson, and S. Giuliani-Leonardi for their contributions to this report.

ACI encourages the development and appropriate use of new and emerging technologies through the publication of the Emerging Technology Series. This series presents information and recommendations based on available test data, technical reports, limited experience with field applications, and the opinions of committee members. The presented information and recommendations, and their basis, may be less fully developed and tested than those for more mature technologies. This report identifies areas in which information is believed to be less fully developed, and describes research needs. The professional using this document should understand the limitations of this document and exercise judgment as to the appropriate application of this emerging technology.

Fiber reinforcement has emerged as an alternative to traditional reinforcing bars and welded wire mesh reinforcement for precast concrete tunnel segments. Due to significantly improved post-cracking behavior and crack control characteristics, fiber-reinforced concrete (FRC) segments offer advantages over tradition-

ally reinforced concrete segments such as saving cost and reducing production time while developing a more robust product with improved handling and long-term durability. Specific guidance on the design of fiber-reinforced precast concrete tunnel segments is needed for this emerging technology. This document offers general information on the history of FRC precast segments from tunneling projects throughout the world; a procedure for structural analysis and design based on governing load cases; and a description of the material parameters, tests, and analyses required to complete the design. The proposed guidelines are based on the knowledge gained from experimental research, analytical work, and the experience gained on numerous FRC precast tunnel projects.

Keywords: crack widths; earth pressure; fibers; fiber-reinforced concrete; grout pressure; hydrostatic pressure; lining; precast segment; stripping; surcharge load; thrust jack forces; tunnel.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

1.1—Introduction, p. 2

1.2—Scope and limitations, p. 3

1.3—Applications and uses in existing tunnels, p. 3

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

ACI 544.7R-16 was adopted and published January 2016.

Copyright © 2016, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording, or by any information storage or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

Documents
Document Sharing Hub



CHAPTER 2—NOTATION AND DEFINITIONS, p. 3

- 2.1—Notation, p. 3
- 2.2—Definitions, p. 6

CHAPTER 3—DESIGN PHILOSOPHY, p. 6

- 3.1—Fiber-reinforced concrete design codes, standards, and recommendations, p. 6
- 3.2—Governing load cases and load factors, p. 7
- 3.3—Design approach, p. 7

CHAPTER 4—DESIGN FOR PRODUCTION AND TRANSIENT STAGES, p. 8

- 4.1—Load Case 1: Segment stripping, p. 8
- 4.2—Load Case 2: Segment storage, p. 9
- 4.3—Load Case 3: Segment transportation, p. 10
- 4.4—Load Case 4: Segment handling, p. 10

CHAPTER 5—DESIGN FOR CONSTRUCTION STAGES, p. 11

- 5.1—Load Case 5: Tunnel-boring machine thrust jack forces, p. 11
- 5.2—Load Case 6: Tail skin back-grouting pressure, p. 14
- 5.3—Load Case 7: Localized back grouting (secondary grouting) pressure, p. 17

CHAPTER 6—DESIGN FOR SERVICE STAGES, p. 18

- 6.1—Load Case 8: Earth pressure, groundwater, and surcharge loads, p. 18
- 6.2—Load Case 9: Longitudinal joint bursting load, p. 21
- 6.3—Load Case 10: Loads induced due to additional distortion, p. 22
- 6.4—Load Case 11: Other loads, p. 23

CHAPTER 7—MATERIAL PARAMETERS FOR DESIGN, p. 23**CHAPTER 8—TESTS AND PERFORMANCE EVALUATION, p. 23**

- 8.1—Material parameters, tests, and analyses, p. 23
- 8.2—Full-scale tests, p. 24

CHAPTER 9—HYBRID REINFORCEMENT FOR TUNNEL LININGS, p. 25**CHAPTER 10—DESIGN EXAMPLES, p. 27**

- 10.1—Monte Lirio tunnel in Panama, p. 27
Design summary, p. 27
- 10.2—Barcelona Metro Line 9, p. 29

CHAPTER 11—REFERENCES, p. 30

- Authored documents, p. 30

APPENDIX A—CALCULATION OF AXIAL FORCE-BENDING MOMENT INTERACTION DIAGRAM, p. 33**CHAPTER 1—INTRODUCTION AND SCOPE****1.1—Introduction**

Precast concrete segments are installed to support the tunnel bore behind the tunnel-boring machine (TBM) in soft ground and weak rock applications. The TBM advances by reacting against the completed rings of precast concrete segments that typically provide both the initial and final ground support as part of a one-pass liner system. These segments are typically designed to resist the permanent loads from the ground and groundwater, as well as the temporary loads from production, transportation, and construction. Tunnel segments are generally reinforced to resist the tensile stresses at both the serviceability limit state (SLS) and the ultimate limit states (ULS). With traditional reinforcing bar, a significant amount of labor is needed to assemble the cages and place the reinforcing bar.

Fiber-reinforced concrete (FRC) can be used to enhance handling and placement of precast concrete segments with the added benefit of reducing job-site labor requirements. FRC considerably improves the post-cracking behavior, defined as toughness (di Prisco et al. 2009), and it has better crack control characteristics than conventional steel-bar-reinforced concrete (Minelli et al. 2011; Tiberti et al. 2014). The use of FRC generally results in smaller crack widths and improved durability over the life of the structure. Because of the uniform dispersion of fibers throughout the segment, including the area around the segment face, fiber reinforcement effectively resists the bursting and spalling stresses that develop during the TBM jacking process. de Waal (1999) and Schnütgen (2003) highlight the beneficial effect of FRC in the presence of concentrated loads and bursting. Furthermore, the presence of fiber in the concrete matrix increases the fatigue and impact resistance of the segments that help mitigate against unintentional impact loads during segment handling and tunnel construction operations (di Prisco and Felicetti 2004).

Reinforcing bar is efficient for resisting localized stresses in the concrete segment such as stresses due to concentrated loads during production. The distributed stresses such as stresses due to earth pressure and groundwater loads at final service stage, however, are better dealt with by fiber reinforcement. Because both localized and distributed stresses are generally present in tunnel linings, segments can be manufactured using a combination of conventional reinforcing bar and fiber reinforcement—that is, a hybrid system. For larger-diameter tunnels with high internal forces, a combined solution of fibers and reinforcing bar may present an ideal solution (Plizzari and Tiberti 2006, 2007; de la Fuente et al. 2012). Using current technology with high-strength concrete segments, tunnel rings of more than 23 ft (7 m) in diameter have been used successfully (Abbas et al. 2014). Examples include Grosvenor Coal Mine, Channel Tunnel Rail Link Tunnel, and Blue Plains Tunnel with internal diameters of 23, 23.5, and 23 ft (7, 7.15, and 7 m), respectively.

The slenderness of the tunnel segment (λ), defined as the ratio between the breadth or curved length of segment along

its centroid (developed segment lengths) and its thickness, is a key parameter to determine when fibers can be used as the only source of reinforcement in the concrete tunnel segments. When the slenderness of a segment is higher than 10, it is generally necessary to adopt a hybrid reinforcement of fibers and conventional bars; however, **Beño and Hilar (2013)** have proposed to increase the slenderness limit up to 12 to 13 using the pilot test tunnel segments used in Prague Metro Line A Extension in Czech Republic as a model. Full-scale tests are needed to validate the usage of fibers with such slenderness conditions.

1.2—Scope and limitations

The fiber-reinforced concrete (FRC) segment designers should be provided with a clear and simple approach using specified post-crack residual tensile strength σ_p (ACI 544.8R) and specified compressive strength f'_c . This report proposes a procedure for designing FRC tunnel segments to withstand all the appropriate temporary and permanent load cases occurring during the construction and design life of tunnels. This procedure is based on the available design codes, standards, and guidelines. Application of this approach is summarized in this document. Full-scale bending tests are also discussed to evaluate the segment performance during each stage of its design life to include stripping, storage handling, transportation, and the in-service load condition due to earth pressure, groundwater, and surcharge loads. Other full-scale tests performed on the precast segments include thrust tests to reproduce the tunnel boring machine (TBM) action on the segment during the jacking process.

This report is focused on the analysis, design, and manufacturing of FRC segments of one-pass precast segmental lining used with TBM-bored tunnels. The design methods presented can be applied to tunnels of different types such as road, railway, and subway tunnels; headrace, water supply, and wastewater tunnels; and service, gas pipeline, and power cable tunnels. Two-pass lining systems, however, can also benefit from the proposed design procedure.

This document does not address the actions of TBM gantries, thermal variations, fire loads, or internal loads such as train loads within tunnels. Also, further research is needed to establish design checks for concrete breakout strength around bolts and dowels, and resistance against punching shear force in the proximity of stack support at storage phase.

The design procedures presented herein have been developed for steel fibers, and any extrapolation to synthetic or other types of fibers reported in **ASTM C1116/C1116** should be confirmed by repeating small-scale (**ASTM C1609/C1609M**; **BS EN 14651**) and full-scale bending, point load, and cantilever tests explained in **Chapter 8** to show that static and long-term properties are adequately characterized.

Typical volume fraction of steel fibers used in FRC tunnel segments does not exceed 0.5 percent, which typically results in a tensile strain-softening response (ACI 544.8R) of the material. Therefore, this report only covers properties, analysis, and design methodologies of tensile strain-softening FRCs, and not tensile strain-hardening materials (ACI 544.8R). Note that a deflection-hardening response

under flexural tests can be achieved using conventional fiber dosage rates, which is desired due to improved crack control characteristics of concrete materials (ACI 544.8R).

1.3—Applications and uses in existing tunnels

Since 1982, fiber-reinforced concrete (FRC) has been used in numerous projects around the world and is the preferred material for the construction of tunnel precast segmental lining (**de la Fuente et al. 2012, 2013**; **Hilar and Beño 2012**; **Hansel and Guirguis 2011**). FRC technology has developed in recent years with the introduction of high-strength concrete, allowing the use of fibers as the sole reinforcement system for more challenging conditions on larger-diameter tunnel projects (**Barwart et al. 2013**). In other cases, fiber and reinforcing bars have been used in conjunction to reinforce the tunnel segments (**de la Fuente et al. 2012**). Tunnels with different sizes with internal diameters ranging between 7.2 and 37.4 ft (2.2 and 11.4 m) have been built using fiber reinforcement (**Hilar and Beño 2012**). Minimum and maximum thickness of the FRC precast segments in existing tunnels are 6 and 16 in. (0.15 and 0.40 m), respectively (**de la Fuente et al. 2012**).

A number of these projects are shown in Table 1.3 and include water supply, waste water, gas pipeline, power cable, subway, railway, and road tunnels. FRC segments shown in Table 1.3 are reinforced primarily with steel fibers as the main source of reinforcement. In many of the smaller-diameter tunnel projects, the precast concrete segmental liners were reinforced only with steel fibers using dosage rates between 40 and 100 lb/yd³ (25 and 60 kg/m³).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_d	= load distribution area inside segment under thrust jack forces, in. ² (mm ²)
A_g	= gross area of concrete section, in. ² (mm ²)
A_j	= area of contact zone between jack shoes and the segment face, in. ² (mm ²)
A_s	= required area of reinforcing bars, in. ² (mm ²)
a	= distance from edge of vacuum lift pad to edge of segment in the load case of stripping, or dimension of final spreading surface under thrust jack forces, in. (mm)
a_l	= transverse length of contact zone between jack shoes and the segment face, in. (mm)
a_t	= transverse length of stress distribution zone at the centerline of segment under thrust jack forces, in. (mm)
b	= width of tunnel segment, or width of tested specimen, ft (m)
C_c	= compression force in the concrete section, lbf (N)
C_t	= tensile force in the section due to fiber reinforcement, lbf (N)
D_e	= external diameters of the tunnel segmental lining, ft (m)
D_i	= internal diameter of the tunnel segmental lining, ft (m)

Table 1.3—Tunnels lined by FRC precast segments (de la Fuente et al. 2012, 2013; Hilar and Beno 2012; Hansel and Guirguis 2011)

Tunnel name	Year	Country	Function	D_i , ft (m)	h_i , in. (m)	D_i/h_i	Steel fiber content, lb/yd ³ (kg/m ³)	Reinforcing bars used
Metrosud	1982	Italy	Subway	19 (5.8)	12 (0.30)	19.3	NA*	No
Fanaco	1989	Italy	Water supply	10 (3.0)	8 (0.20)	15.0	NA*	No
Heathrow Baggage Handling	1993	England	Service	15 (4.5)	6 (0.15)	30.0	50 (30)	No
Heathrow Express	1994	England	Railway	18.7 (5.7)	9 (0.22)	25.9	50 (30)	No
Napoli metro	1995	Italy	Subway	19 (5.8)	12 (0.30)	19.3	67 (40)	No
Lesotho Highlands	1995	South Africa	Water supply	15 (4.5)	12 (0.30)	15.0	84 (50)	No
Hachinger	1998	Germany	Water supply	7.2 (2.2)	7 (0.18)	12.2	NA*	No
Second Heinenoord	1999	Netherlands	Road	25 (7.6)	14 (0.35)	21.7	NA*	No
Jubilee Line	1999	England	Subway	15 (4.5)	8 (0.20)	22.3	50 (30)	No
Trasvases Manabi (La Esperanza)	2001	Ecuador	Water supply	11.5 (3.5)	8 (0.20)	17.5	50 (30)	No
Essen	2001	Germany	Subway	24 (7.3)	14 (0.35)	20.9	NA*	No
Sorenberg	2002	Switzerland	Gas pipeline	12.5 (3.8)	10 (0.25)	15.2	67 (40)	No
Canal de Navarra	2003	Spain	Water supply	17.7 (5.4)	10 (0.25)	21.6	NA*	No
Oënzberg-TBM	2003	Switzerland	Railway	37.4 (11.4)	16 (0.40)	28.5	50 (30)	Yes
Oënzberg-Shield	2003	Switzerland	Railway	37.4 (11.4)	16 (0.40)	28.5	100 (60)	No
Barcelona Metro Line 9 – Can Zam Stretch	2003	Spain	Subway	35.8 (10.9)	14 (0.35)	31.1	100 (60)	Yes
Hofolding Stollen	2004	Germany	Water supply	9.5 (2.9)	7 (0.18)	16.1	67 (40)	No
Heathrow Express Extension (HexEx)	2005	England	Railway	18.7 (5.7)	9 (0.22)	25.9	50 (30)	No
San Vicente	2006	U.S.	Water supply	10.5 (3.2)	7 (0.18)	17.8	50 (30)	No
Heathrow– SWOT	2006	England	Water supply	9.5 (2.9)	8 (0.20)	14.5	50 (30)	No
Barcelona Metro Line 9 – Stretch I	2006	Spain	Subway	27.6 (8.4)	13 (0.32)	26.3	50 (30) and 42 (25)	Yes
Lötschberg	2007	Switzerland	Pilot	14.8 (4.5)	9 (0.22)	20.5	NA*	No
Valencia Metro Line 1	2007	Venezuela	Subway	27.6 (8.4)	16 (0.40)	21.0	67 (40)	Yes
Channel Tunnel Rail Link Tunnel	2007	England	Railway	23.5 (7.15)	14 (0.35)	20.4	50 (30)	No
Gold Coast Desalination Plant	2008	Australia	Water supply	11.2 (3.4)	8 (0.20)	17.0	60 (35)	No
Big Walnut Sewer	2008	U.S.	Waste water	12 (3.7)	9 (0.23)	16.1	60 (35)	Yes
Heathrow – PiccEx	2008	England	Subway	14.8 (4.5)	6 (0.15)	30.0	50 (30)	No
Hobson Bay	2009	New Zealand	Wastewater	12 (3.7)	10 (0.25)	14.8	67 (40)	No
Sao Paulo Metro Line 4	2009	Brazil	Subway	27.6 (8.4)	14 (0.35)	24.0	60 (35)	No
Copenhagen District Heating Tunnel	2009	Denmark	Water supply	13.8 (4.2)	12 (0.30)	14.0	60 (35)	No
Docklands Light Railway (DLR) Extension	2009	England	Railway	17.4 (5.3)	10 (0.25)	21.2	NA*	No
Fontsanta–Trinitat Interconnection	2010	Spain	Water supply	17 (5.2)	8 (0.20)	26.0	42 (25)	Yes
Clem Jones – Clem 7	2010	Australia	Road	36.7 (11.2)	16 (0.40)	28.0	62 (37)	Yes
Ems-Dollard Crossing	2010	Germany-Netherlands	Gas pipeline	9.8 (3.0)	10 (0.25)	12.0	NA*	No
City West Cable Tunnel (CWCT)	2010	Australia	Power cable	8.2 (2.5)	8 (0.20)	12.5	NA*	No
Adelaide Desalination Plant	2010	Australia	Water supply	9.2 (2.8)	8 (0.20)	14.0	60 (35)	No
FGC Terrassa	2010	Spain	Railway	19.7 (6.0)	12 (0.30)	20.0	42 (25)	Yes
Brightwater East	2011	U.S.	Wastewater	16.7 (5.1)	10 (0.26)	19.6	60 (35)	No
Brightwater Central	2011	U.S.	Wastewater	15.4 (4.7)	13 (0.33)	14.2	67 (40)	No
Brightwater West	2011	U.S.	Wastewater	12.1 (3.7)	10 (0.26)	14.2	60 (35)	No
East side CSO	2011	U.S.	Wastewater	22 (6.7)	14 (0.36)	18.6	NA*	No
Victorian Desalination Plant	2011	Australia	Water supply	13.1 (4.0)	9 (0.23)	17.4	NA*	No
Monte Lirio	2012	Panama	Water supply	10.5 (3.2)	10 (0.25)	12.8	67 (40)	No
Pando	2012	Panama	Water supply	9.8 (3.0)	10 (0.25)	12.0	67 (40)	No
El Alto	2013	Panama	Water supply	19 (5.8)	14 (0.35)	16.6	67 (40)	No
Wehrhahn	2014	Germany	Subway	27.2 (8.3)	12 (0.30)	27.7	67 (40)	No
STEP Abu Dhabi Lot T-02	2014	UAE	Wastewater	20.7 (6.3)	11 (0.28)	22.5	67 (40)	Yes
Grosvenor Coal Mine	2014	Australia	Mining	23 (7.0)	14 (0.35)	19.7	60 (36)	No
San Francisco Central Subway	2014	U.S.	Subway	17.8 (5.4)	11 (0.28)	19.4	45 (27)	Yes
Blue Plains Tunnel	2015	U.S.	Wastewater	23 (7.0)	14 (0.35)	19.7	60 (36)	No
Lee Tunnel Sewer	UC†	England	Wastewater	23.6 (7.2)	14 (0.35)	20.6	NA*	No
Brenner Base Tunnel	UC†	Austria	Railway	18.4 (5.6)	8 (0.20)	28.0	NA*	Yes

*NA: Not available.

†UC: Under construction.



d = thickness of tested specimen, or total width of the segment cross section, in. (mm)	f_t = specified splitting tensile strength, psi (MPa)
d_1 = length of load transfer zone for the case of longitudinal joint bursting load, in. (mm)	g = self-weight of the segments per unit length, lbf/in. (N/mm)
d_{burst} = centroidal distance of bursting force from the face of section, in. (mm)	H = overburden depth, ft (m)
d_k = width of the hinge neck for the case of longitudinal joint bursting load, in. (mm)	H_w = groundwater depth, ft (m)
d_s = distributed width of tension block inside the segment for the case of longitudinal joint bursting, in. (mm)	h = thickness of tunnel segment, in. (mm)
E = modulus of elasticity of concrete, psi (MPa)	h_{anc} = length of contact zone between jack shoes and the segment face, in. (mm)
e = eccentricity, in. (mm)	I = moment of inertia of FRC segment, in ⁴ . (mm ⁴)
e_{anc} = eccentricity of jack pads with respect to the centroid of cross section, or maximum total eccentricity in longitudinal joints consisting of force eccentricity and eccentricity of load transfer area, in. (mm)	k = coefficient of subgrade reaction, lb/ft ³ (kg/m ³)
F = forces acting on bottom segment due to self-weight of segments positioned above, lbf (N)	L = distance between the supports, in. (mm)
F_{sd} = bursting tensile forces developed close to longitudinal joints, lbf (N)	M_n = nominal resistance bending moment, lbf·ft (N·m)
$F_{sd,r}$ = spalling tensile forces developed close to longitudinal joints, lbf (N)	N_{Ed} = maximum normal force due to permanent ground, groundwater and surcharge loads, lbf (N)
$F_{sd,2}$ = secondary tensile forces developed close to longitudinal joints, lbf (N)	P_0 = surcharge load, lbf (N)
F_y = yield stress of required reinforcing bars, psi (MPa)	P_{e1} = vertical earth pressure at crown of lining applied to the elastic equation method, psi (MPa)
f_1 = first peak flexural strength, psi (MPa)	P_{e2} = vertical earth pressure at invert of lining applied to the elastic equation method, psi (MPa)
f_{bot} = stress at the extreme bottom fiber of concrete section, psi (MPa)	P_g = segment dead load, psi (MPa)
f_c' = specified compressive strength of fiber-reinforced concrete segment, psi (MPa)	P_{pu} = factored jacking force applied on each jack pad in circumferential joints, or maximum factored normal force from the final service loads transferred in longitudinal joints, psi (MPa)
f_{cd} = concrete design compressive strength, psi (MPa)	P_{w1} = vertical water pressure at crown of lining applied to the elastic equation method, psi (MPa)
f_{ck} = concrete characteristic compressive strength, psi (MPa)	P_{w2} = vertical water pressure at invert of lining applied to the elastic equation method, psi (MPa)
f_{ctd} = fiber-reinforced concrete design tensile strength, psi (MPa)	q_{e1} = horizontal earth pressure at crown of lining applied to the elastic equation method, psi (MPa)
f_{co}' = compressive strength of partially loaded concrete surface, psi (MPa)	q_{e2} = horizontal earth pressure at invert of lining applied to the elastic equation method, psi (MPa)
f_{150}^D = residual flexural strength at net deflection of $L/150$, psi (MPa)	q_{w1} = horizontal water pressure at crown of lining applied to the elastic equation method, psi (MPa)
$f_{150}^{D_s}$ = specified residual flexural strength at net deflection of $L/150$, psi (MPa)	q_{w2} = horizontal water pressure at invert of lining applied to the elastic equation method, psi (MPa)
f_{150r}^D = required average residual flexural strength at net deflection of $L/150$, psi (MPa)	R = radius from centerline of lining, ft (m)
f_{600}^D = residual flexural strength at net deflection of $L/600$, psi (MPa)	r_o = radius of excavated tunnel, ft (m)
$f_{600}^{D_s}$ = specified residual flexural strength at net deflection of $L/600$, psi (MPa)	S = distance between stack supports and free edge of segments in the load case of segment storage, ft (m)
f_{600r}^D = required average residual flexural strength at net deflection of $L/600$, psi (MPa)	s_s = sample standard deviations of test results
f_{Ftu} = fiber-reinforced concrete tensile strength at ultimate limit state, psi (MPa)	T_{burst} = bursting force, lbf (N)
f_{R1} = residual flexural strength of FRC beam corresponding to crack mouth opening displacement of 0.02 in. (0.5 mm), psi (MPa)	w = segment self-weight, plf (kg/m)
f_{R3} = residual flexural strength of fiber-reinforced concrete beam corresponding to crack mouth opening displacement of 0.1 in. (2.5 mm), psi (MPa)	y = distance from extreme tension fiber to the neutral axis, in. (mm)
	y_c = distance from extreme compression fiber to centroid of equivalent compression force in the section, in. (mm)
	β = dimension of the loaded surface under thrust jack forces according to Iyengar diagram, in. (mm)
	$\Delta P_{g, invert}$ = vertical gradient of radial grout pressure between the crown and invert of tunnel, psi (MPa)
	δ = displacement of lining applied to the elastic equation method, in. (mm)
	δ_d = diametrical distortion, in. (mm)
	ϵ_{cu} = ultimate tensile strain
	ϵ_{ru} = ultimate compressive strain
	ϕ = strength reduction factor

- γ = material safety factor
 λ = slenderness defined as the ratio between the developed segment lengths and its thickness
 θ = angle from crown in the elastic equation method, radians
 $\rho_{concrete}$ = specific weight of concrete, lb/ft³ (kg/m³)
 ρ_{eq} = equivalent specific weight of grout, lb/ft³ (kg/m³)
 $\sigma_{c,j}$ = compressive stresses developed under jack pads because of axial effects of thrust jack forces, psi (MPa)
 σ_{cm} = fully spread compressive stress in method of the Iyengar diagram, psi (MPa)
 σ_{cx} = bursting tensile stresses using the Iyengar diagram, psi (MPa)
 σ_p = specified post-crack residual tensile strength of fiber-reinforced concrete segment, psi (MPa)
 τ_{yield} = shear yield strength of grout, psi (MPa)

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology (<https://www.concrete.org/store/productdetail.aspx?ItemID=CT13>) for a comprehensive list of definitions. Definitions provided herein complement that resource.

annular gap—space between the surrounding ground and the outer surface of the segments.

circumferential joint—joint approximately perpendicular to the tunnel axis between two adjacent segment rings.

connections—devices for temporary or permanent connection of two segments or segment rings in the longitudinal and circumferential joints.

crosscut—connecting structure between two tunnel tubes or between a tunnel tube and the ground surface or a shaft, with special passages in the connecting area of the main tube.

crown—highest part of a tunnel in cross section.

extrados—outer surface of the segment or the segment ring on the side in contact with the ground.

ground—soil, rock, and fill in place prior to the execution of the construction works.

intrados—inner surface of the segment or the segment ring on the tunnel side.

invert—lowest part of a tunnel in cross section.

overburden—ground load overlying the tunnel.

portal—entrance from the ground surface to a tunnel.

segment—curved prefabricated elements that make up a ring of support or lining.

segment gasket—sealing system consisting of sealing strips placed in one or more layers around the individual segment, ensuring permanent sealing of the tunnel tube against the ingress of water from the surrounding ground.

segment thickness—radial distance between the inner and outer sides of a segment.

shaft—elongated vertical linear excavation.

shield—steel tube, usually cylindrical, shaped to fit the excavation line of a tunnel.

soft ground—residual soil or deteriorated rock with limited compressive strength and stand-up time.

springline—opposite ends of the horizontal centerline of tunnel excavation and the beginning of noticeable movements of the ground.

stripping—process of removing a precast concrete segment from the form in which it was cast.

tail void—annular space between the outside diameter of the shield and the outside of the segmental lining.

thrust jacks—hydraulic jacks serving to transmit the thrust forces of the tunnel boring machine to the segment ring, facilitating installation, or both.

tunnel cover—perpendicular distance to nearest ground surface from the tunnel exterior.

two-pass lining—tunnel lining consisting of two shells with different structural and constructional requirements that are produced in independent operations and with different construction methods.

CHAPTER 3—DESIGN PHILOSOPHY

3.1—Fiber-reinforced concrete design codes, standards, and recommendations

Fiber-reinforced concrete (FRC) precast tunnel segments have been designed using constitutive laws recommended by international design guides, codes, and standards such as **German Concrete Association DBV (1992)**, **RILEM TC 162-TDF, CNR DT 204/2006, EHE-08, fib Model Code 2010 (International Federation for Structural Concrete 2013)**, and **ACI 544.8R**. These documents propose stress-crack width or stress-strain constitutive laws of FRC as a linear post-cracking behavior (hardening or softening) or as a rigid perfectly plastic behavior based on bending test results. Alternatively, an approach using nonlinear fracture mechanics can be adapted to analyze cracking phenomena (**Hillerborg et al. 1976**).

In ACI 544.8R, there are models that can be adopted to obtain required constitutive laws for the calculation of axial force/bending moment interaction diagrams for use with FRC precast tunnel segments. This document recommends the ACI 544.8R method that uses results of standard beam tests such as **ASTM C1609/C1609M** and **BS EN 14651** to determine post-crack residual tensile strength as one of the key design parameters for FRC tunnel segments.

In addition to beam tests, panel or plate tests including square panels such as **European Federation of Producers and Applicators of Specialist Products for Structures (1999)** panel test and round panels such as **ASTM C1550** can be used as alternatives to evaluate tensile properties of FRC materials. These tests, however, only evaluate system resistance properties and do not provide section design properties. Small round panel tests have been recently proposed (**Minelli and Plizzari 2011**) to overcome difficulties associated with heavyweight round panel specimens.

Resulting shear forces developed in the lining under the earth pressure and groundwater loads and the grouting pressure can be entirely taken by the concrete containing fiber reinforcement (**Plizzari and Tiberti 2007**). It can be stated that shear forces are generally small; accordingly, the

reinforcement provided by fibers generally satisfies requirements for tunnel segments (Tiberti 2009).

3.2—Governing load cases and load factors

The current practice in the tunnel industry is to design segmental tunnel lining for the following load cases, which occur during segment manufacturing, transportation, installation, and service conditions:

- a) Production and transient stages (Chapter 4)
 - i. Load Case 1: segment stripping
 - ii. Load Case 2: segment storage
 - iii. Load Case 3: segment transportation
 - iv. Load Case 4: segment handling
- b) Construction stages (Chapter 5)
 - i. Load Case 5: tunnel-boring machine (TBM) thrust jack forces
 - ii. Load Case 6: tail skin back-grouting pressure
 - iii. Load Case 7: localized back-grouting (secondary grouting) pressure
- c) Service stages (Chapter 6)
 - i. Load Case 8: earth pressure, groundwater, and surcharge loads
 - ii. Load Case 9: longitudinal joint bursting load
 - iii. Load Case 10: loads induced due to additional distortion
 - iv. Load Case 11: other loads (for example, earthquake, fire, and explosion)

In the strength design procedure, the required strength U is expressed in terms of factored loads shown in Table 3.2 for presented governing load cases. In this document, the 11 aforementioned load cases are divided into three categories: production and transient loads; construction loads; and service loads. The resulting axial forces, bending moments, and shear forces are used to design concrete and reinforcement. Because the resistance of the fiber-reinforced concrete (FRC) elements is determined on the basis of inelastic behavior, a proper design procedure needs to account for the significant post-crack residual tensile strength provided by the fibers.

3.3—Design approach

The design engineer should use load and resistance factor design (LRFD) method to design fiber-reinforced concrete (FRC) precast tunnel segments. LRFD is a design philosophy that takes into account the variability in the prediction of loads and the variability in the properties of structural elements. LRFD employs specified limit states to achieve its objectives of constructability, safety, and serviceability.

Even though force effects may be often determined using elastic analyses, the resistance of elements using LRFD design methods is determined on the basis of inelastic behavior. For FRC components under compression, specified compressive strengths f'_c similar to those for reinforced concrete sections are adopted for design. When under flexure or tension, however, inelastic flexural resistance at the ultimate limit state (ULS) should be used. This parameter is calculated based on residual strength of a standard beam at net midspan deflection of $L/150$ (f_{150}^D), defined as end-point

Table 3.2—Required strength U expressed in terms of factored loads for governing load cases

Load case	Required strength U
Load Case 1: stripping	$U = 1.4w$
Load Case 2: storage	$U = 1.4(w + F)$
Load Case 3: transportation	$U = 1.4(w + F)$
Load Case 4: handling	$U = 1.4w$
Load Case 5: thrust jack forces	$U = 1.2J$
Load Case 6: tail skin grouting	$U = 1.25(w + G)$
Load Case 7: secondary grouting	$U = 1.25(w + G)$
Load Case 8: earth pressure and groundwater load	$U = 1.25(w + W_{Ap}) + 1.35(EH + EV) + 1.5ES$
Load Case 9: longitudinal joint bursting	$U = 1.25(w + W_{Ap}) + 1.35(EH + EV) + 1.5ES$
Load Case 10: additional distortion	$U = 1.4M_{distortion}$

Notes: w is self-weight; F is self-weight of segments positioned above; J is TBM jacking force; G is grout pressure; W_{Ap} is groundwater pressure; EV is vertical ground pressure; EH is horizontal ground pressure; ES is surcharge load; and $M_{distortion}$ is additional distortion effect.

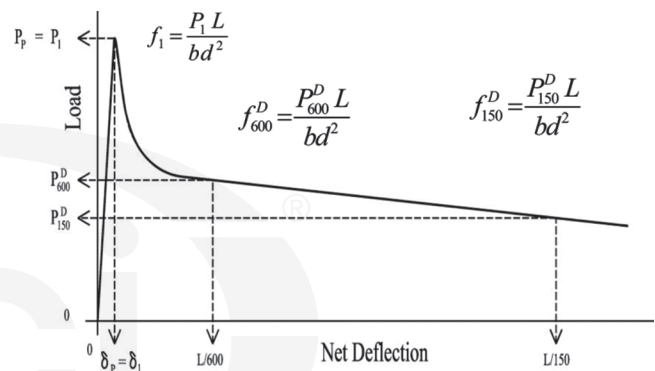


Fig. 3.3a—Definition of residual flexural parameters for FRC beams by ASTM C1609/C1609M.

deflection per ASTM C1609/C1609M. For instance, on a typical beam with a cross section of 6 x 6 in. (150 x 150 mm) and a span of 18 in. (450 mm), the end-point deflection is $18/150 = 0.12$ in. (450/150 = 3 mm). *fib* Model Code 2010 (International Federation for Structural Concrete 2013) and RILEM TC 162-TDF recommend that residual flexural strength corresponding to crack mouth opening of 0.02 in. (0.5 mm) to be used in the calculations for serviceability limit state (SLS). This strength, which corresponds to residual flexural strength at net midspan deflection of $L/600$ (f_{600}^D) according to ASTM C1609/C1609M, should be adopted for serviceability design.

Figure 3.3a shows the deflection limits for the residual flexural parameters of an FRC beam on a typical load-deflection curve. It should be noted that applying raw parameters, such as f_{150}^D , requires caution to prevent overestimating the residual tensile strength when using elastic analysis (Bakhshi et al. 2014). A back-calculation procedure can be adopted to obtain specified residual tensile strength parameters σ_p (Soranakom and Mobasher 2007). For design of FRC elements under bending and axial forces, scale the post-crack flexural strength parameters determined in accordance with standards (ASTM C1609/C1609M; BS EN 14651) by using an adjustment factor λ from 0.37 to 0.75 (Bakhshi et al. 2014; Mobasher et al. 2014; Vande-

walle 2000; Barros et al. 2005; International Federation for Structural Concrete 2013). This factor is used to convert the residual flexural parameters obtained from the standard flexural test to the residual tensile strength used for design (ACI 544.8R). Similar to the recommendations for compressive strength found in ACI 318-11, the required average residual flexural parameters (f_{150r}^D and f_{600r}^D) are based on standard deviations of samples (s_s) and the specified flexural residual strengths (f_{150}^D and f_{600}^D) as follows

$$f_{150r}^D = f_{150}^D + 1.34s_s \quad (3.3a)$$

$$f_{600r}^D = f_{600}^D + 1.34s_s \quad (3.3b)$$

In another approach, the industry accepts arithmetic average of three consecutive residual flexural strength tests as the required average residual flexural strengths (f_{600r}^D and f_{150r}^D) only when no individual test result is more than three times standard deviations ($3s_s$) below the average value. This approach, which is similar to ACI 318-14, 26.12.3.1(b), recommendations for compressive strength f_c' is also acceptable. As it will be discussed in Chapters 4 through 7, the design is performed with respect to the specified residual strength parameter f_{150}^D , while f_{150r}^D is the required residual strength that should be provided by the FRC segment producers.

Note that fiber reinforcement can completely or partially substitute conventional reinforcement at ULS only if the following criteria are fulfilled for all tested samples (International Federation for Structural Concrete 2013)

$$\frac{f_{600}^D}{f_1} > 0.4 \quad (3.3c)$$

$$\frac{f_{150}^D}{f_{600}^D} > 0.5 \quad (3.3d)$$

FRC precast tunnel segments should be designed using load factors and strength reduction factors. For load cases not covered by ACI 318, load factors and load combinations from AASHTO DCRT-1 should be used. For FRC elements, a strength reduction factor of $\phi = 0.70$ should be used for flexure, compression, and shear, and a strength reduction factor of $\phi = 0.65$ should be used for bearing actions of concrete segments. This ϕ factor accounts for the uncertainty of post-crack tensile strength when calculating the design strength of FRC elements. Note that this strength reduction factor is the minimum value recommended by ACI 544.6R.

A common design approach for FRC tunnel segments starts with selecting an appropriate geometry, including selecting thickness, width and length of segments with respect to the size, and loadings of the tunnel. Specified compressive (f_c') and residual flexural strengths (f_{150}^D) of FRC materials are selected next. Using the aforementioned strength reduction factors, the design strength of segments is compared with required strength for factored load cases presented in 3.2.

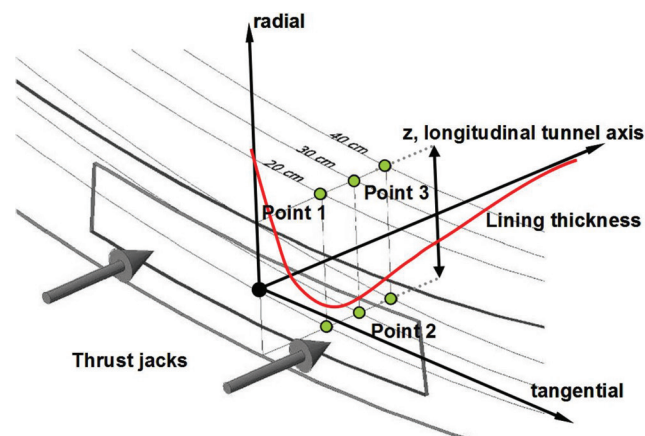


Fig. 3.3b—Distribution of radial bursting stresses along segment width.

Methods of calculation for required strength against these load cases will be explained in the following chapters. For instance, for the load case of thrust jack forces, bursting stresses that are schematically shown in Fig. 3.3b can be calculated using ACI 318 simplified equations for post-tensioned anchorage zones of prestressed sections presented in 5.1.1. Specified post-crack residual tensile strength (σ_p) or specified residual flexural strength (f_{150}^D) with consideration of a scale factor is determined to provide required bursting tensile strength (ACI 544.8R). The geometry, compressive strength, and residual strength of FRC segments should be specified to provide sufficient design strength against all load cases, or otherwise improved.

CHAPTER 4—DESIGN FOR PRODUCTION AND TRANSIENT STAGES

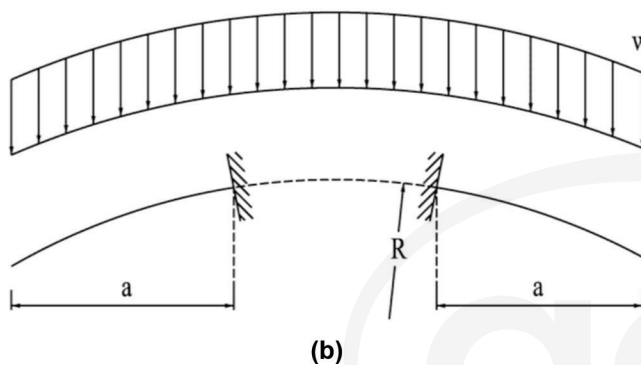
Production and transient loadings include all of the loading stages starting from the time of segment casting up to the time of the segment erection within the tunnel-boring machine (TBM) shield. During these phases, the internal forces and stresses from stripping, storage, transportation, and handling are used for the design of fiber-reinforced concrete (FRC) precast segments. Production and transient loads during these stages result in significant bending moment with no axial forces.

4.1—Load Case 1: Segment stripping

Stripping represents the effect of lifting and stripping of the precast concrete segments from the form at the manufacturing plant once a prescribed strength of concrete has been reached. Two methods are available for the lifting operation: vacuum lifting and mechanical lifting. Figure 4.1(a) shows the stripping phase. The segment can be modeled as two cantilever beams that are loaded under their own self-weight. For ease of transporting the segments, transverse pockets can be designed in the middle of these segments; the cantilever beams would be taken as half the length of the segment. The design has to account for the specified strength of the concrete when the segments are removed from the forms. For instance, on many recent projects, it is common



(a)



(b)

Fig. 4.1—(a) Stripping in the segment manufacturing plant; and (b) forces acting on segments for Load Case 1.

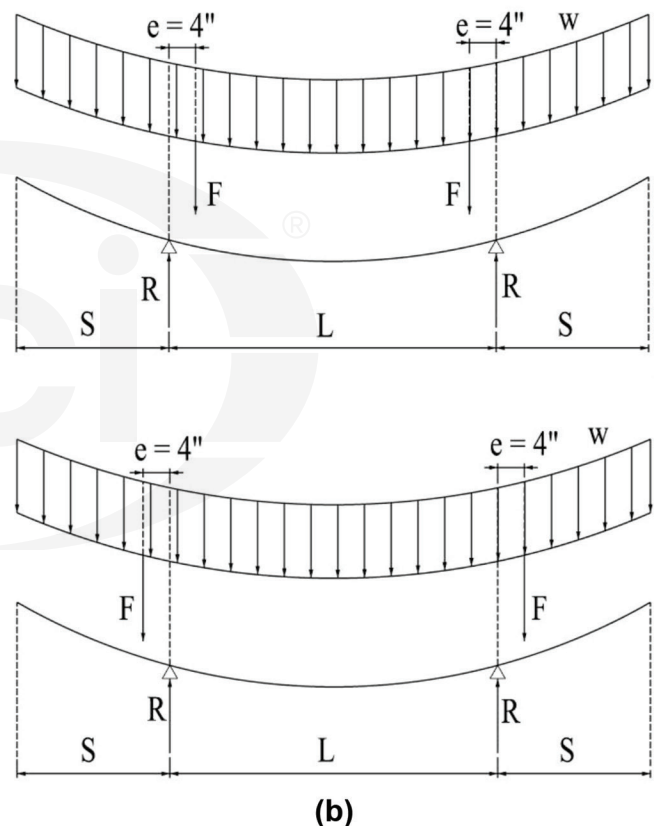
to require that a compressive strength of 2175 psi (15 MPa) be achieved within 3.5 to 4 hours after casting (European International Contractors 2013). Because the stripping process induces bending in the segments, the early-age residual tensile strength of fiber-reinforced concrete (FRC) segments is of significant importance. The desired strength is generally attained between 3 and 4 hours after casting. As shown in Fig. 4.1(b), the self-weight is the only force acting on the segment. As such, the applied load factor is 1.4 as per ACI 318. As part of the design check, the maximum factored bending moment developed in the section is compared against the design moment strength of FRC section. Key design parameters for Load Case 1 are the specified early-age residual tensile or flexural strength (σ_p or f_{t50}^D) and the specified compressive strength f_c' (for example, at 4 hours). Because many fiber configurations rely on bond strength, the residual strengths should be evaluated with early-age samples, not just low-strength concrete.

4.2—Load Case 2: Segment storage

Precast segments are stacked in the stack yard following the stripping process prior to gaining their specified 28-day strength. In some cases, the precast segments are moist-cured for several days. Gaskets, packers, and guiding rods are glued into their designated positions during this phase. As part of the stacking operation, a full ring of segments are



(a)



(b)

Fig. 4.2—(a) Segments piled up within one stack for storage; and (b) forces acting on bottom segment for Load Case 2.

typically stacked together as a single stack. As shown in Fig. 4.2(a), wood blocks are placed at the ground level and in between each of the segments. These blocks serve to support the stacks. Designers often optimize the distance between stack supports (L in Fig. 4.2(b)) and the free edge of the segments (S in Fig. 4.2(b)) to minimize the bending moments in the segments. In an ideal situation, all of the stack supports would be placed perfectly in line with each other; however, in practice, some eccentricity occurs between the upper and lower stack supports. An eccentricity $D + e$ is usually recommended for design. This eccentricity can act

toward either side (inside/outside) of the wood blocks. In addition to the bending moment caused by the self-weight of the bottom segment, the self-weight of the segments above and the eccentricity of the upper stack supports must be taken into account. This stage can be reasonably modeled using a simply supported beam that is loaded under the forces shown in Fig. 4.2(b). All of the forces acting on the segment are dead loads; therefore, a load factor of 1.4 is applied per ACI 318. For this load case, there are no axial forces. As such, the fiber-reinforced concrete (FRC) section is designed to resist only the maximum bending moment. Similar to previous load cases, the key design parameters are the early-age specified residual tensile or flexural strength (σ_p or f'_{150}) and the specified compressive strength f'_c (for example, at 4 hours).

4.3—Load Case 3: Segment transportation

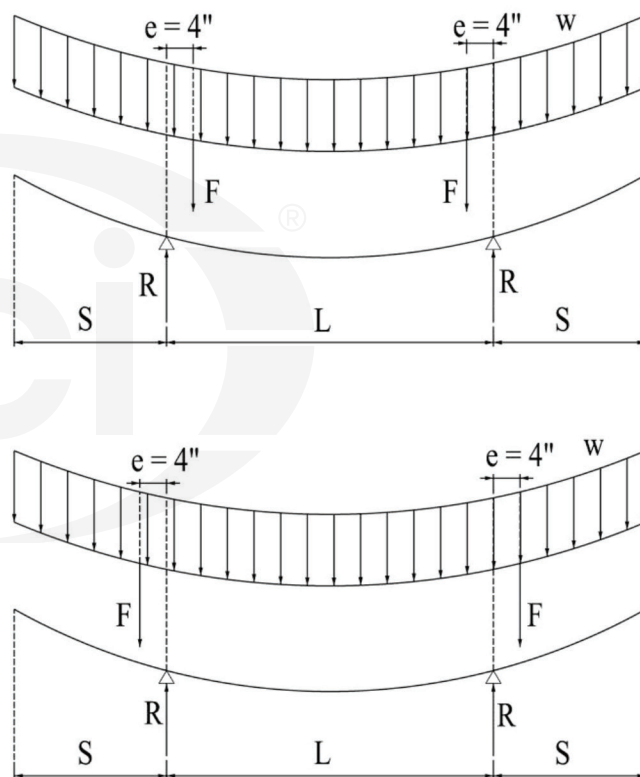
Segments are generally transported to the jobsite as soon as specified compressive and flexural strengths have been achieved in the stack yard. During transportation, the segments generally undergo various types of dynamic shock loading. As shown in Fig. 4.3(a), half of the segments for each ring are usually transported to tunnel-boring machine (TBM) trailing gear. Similar to the storage phase, wood blocks are used between the segments as stack support. The designer generally optimizes the distances between the wood blocks as well as the free edge of the segments to reduce the bending moments in the sections. An eccentricity of 4 in. (0.1 m) is usually recommended for eccentricity effects that may develop due to imperfect alignment of the stack supports. This load case also simulates the load condition that may be induced by forklifts at lift points that are spaced wider than the stack supports. Multiple segments can be picked up together by the forklift. A simply supported beam loaded with the appropriate forces, as shown in Fig. 4.3(b), may be used to represent this load case. In addition to a dead load factor of 1.4 as per ACI 318, a dynamic shock factor of 2.0 is also recommended to simulate the shock effects during transportation (AASHTO DCRT-1). Key parameters for design to resist maximum developed bending moment in this load case are the specified residual tensile or flexural strength (σ_p or f'_{150}) and specified compressive strength f'_c at 28 days.

4.4—Load Case 4: Segment handling

Segment handling from the stack yard onto trucks and rail cars is carried out by specially designed lifting devices such as vacuum lifters. Inside the tunnel-boring machine (TBM), segment handling is also typically performed by similar vacuum lifters. However, other methods such as lifting using slings, typically fixed at quarter-points with an inclination of 45 degrees, may be used occasionally, which results in a different loading scheme. Figure 4.4 shows handling methods common for TBM tunneling applications. Similar to Load Case 1, segments are modeled using cantilever beams. The bending moments from Load Case 1 can be used; however, in addition to the dead load factor of 1.4 as per ACI 318, a dynamic shock factor of 2.0 is recommended to account for



(a)



(b)

Fig. 4.3—(a) Segment transportation to TBM trailing gear; and (b) forces acting on bottom segment for Load Case 3.

the jarring forces acting on segments (AASHTO DCRT-1) during handling. The key design parameters used for calculating flexural strength M_n includes the specified residual or flexural strength (σ_p or f'_{150}) and the specified compressive strength f'_c at 28 days.

Table 4.4 presents a summary of load cases; applied dynamic shock factors, if any; maximum developed bending moments; and key design parameters for the various manufacturing, transportation, and handling stages. Methods for calculating the flexural strength M_n is presented in Appendix