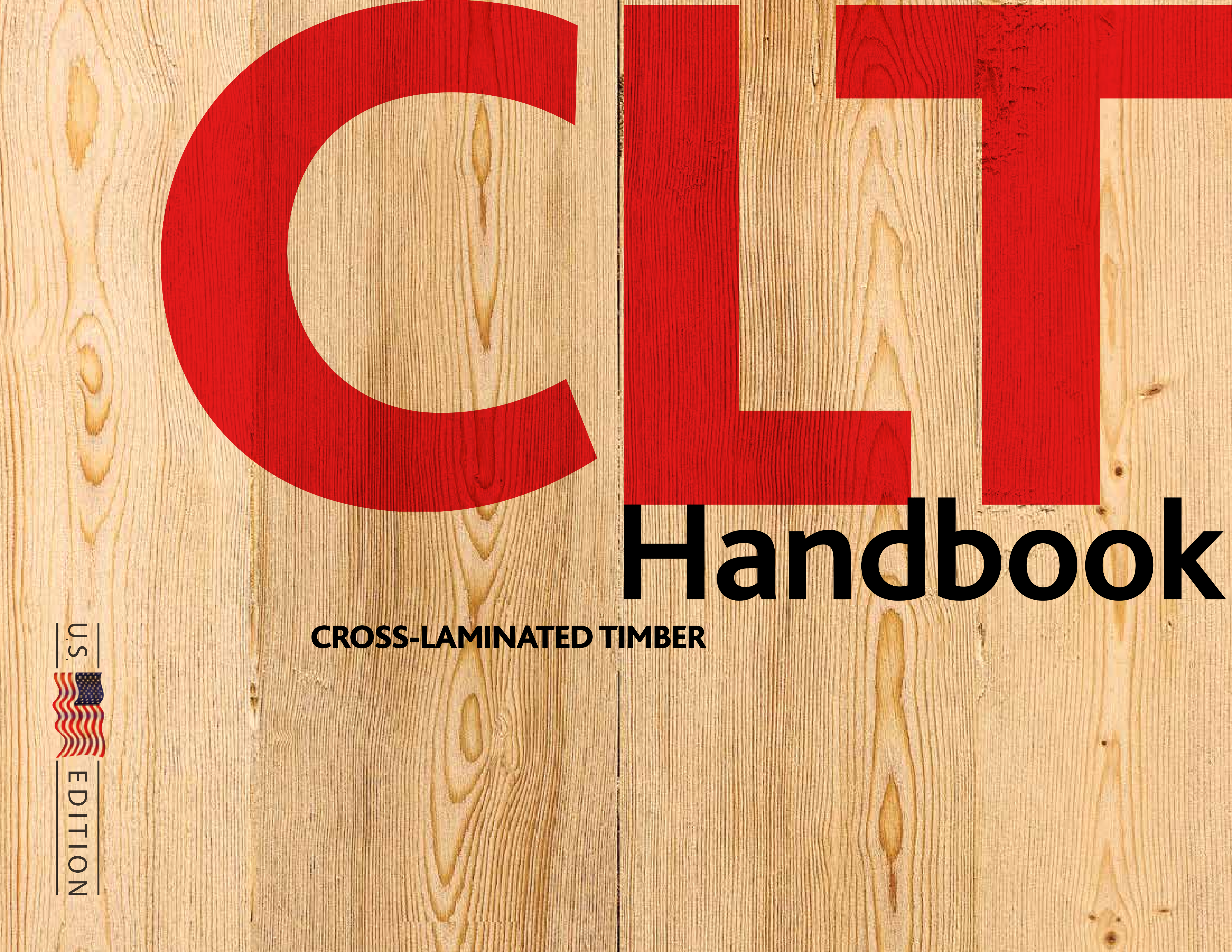

CLT Handbook

CROSS-LAMINATED TIMBER

U.S. EDITION

The U.S. Edition of the CLT Handbook: cross-laminated timber can be electronically downloaded without charge from the website www.masstimber.com. Additional information can be obtained by visiting the websites of FPInnovations, USFPL, American Wood Council (AWC), APA and U.S. WoodWorks. Hard copies can be obtained through AWC (www.awc.org).

The information contained in this Work represents current research results and technical information made available from many sources, including researchers, manufacturers, and design professionals. The information has been reviewed by professionals in wood design including professors, design engineers and architects, and wood product manufacturers. While every reasonable effort has been made to insure the accuracy of the information presented, and special effort has been made to assure that the information reflects the state-of-the-art, none of the above-mentioned parties make any warranty, expressed or implied, or assume any legal liability or responsibility for the use, application of, and/or reference to opinions, findings, conclusions, or recommendations included in this published work, nor assume any responsibility for the accuracy or completeness of the information or its fitness for any particular purpose.

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CLT Handbook

CROSS-LAMINATED TIMBER

Edited by
Erol Karacabeyli, P.Eng., FPInnovations
Brad Douglas, P.E., AWC

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PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber** (CLT)
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry's CLT Steering Committee identified CLT as a great addition to the "**wood product toolbox**" and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

Our very special thanks go to Loren Ross at AWC and Sylvain Gagnon at FPInnovations for their work as project leaders and for their special efforts in gathering the expertise of everyone into a unique document. Special thanks also go to the Working Group, Dr. Borjen Yeh from APA, Dave Kretschmann from the U.S. Forest Products Laboratory, and Lisa Podesto from U.S. WoodWorks. Thanks also to Madeline Leroux for her work on the drawings, Odile Fleury for her help with bibliographic references, and Marie-Claude Thibault for her support in editing and coordination work.

Erol Karacabeyli, P.Eng. and **Brad Douglas**, P.E.
Co-editors
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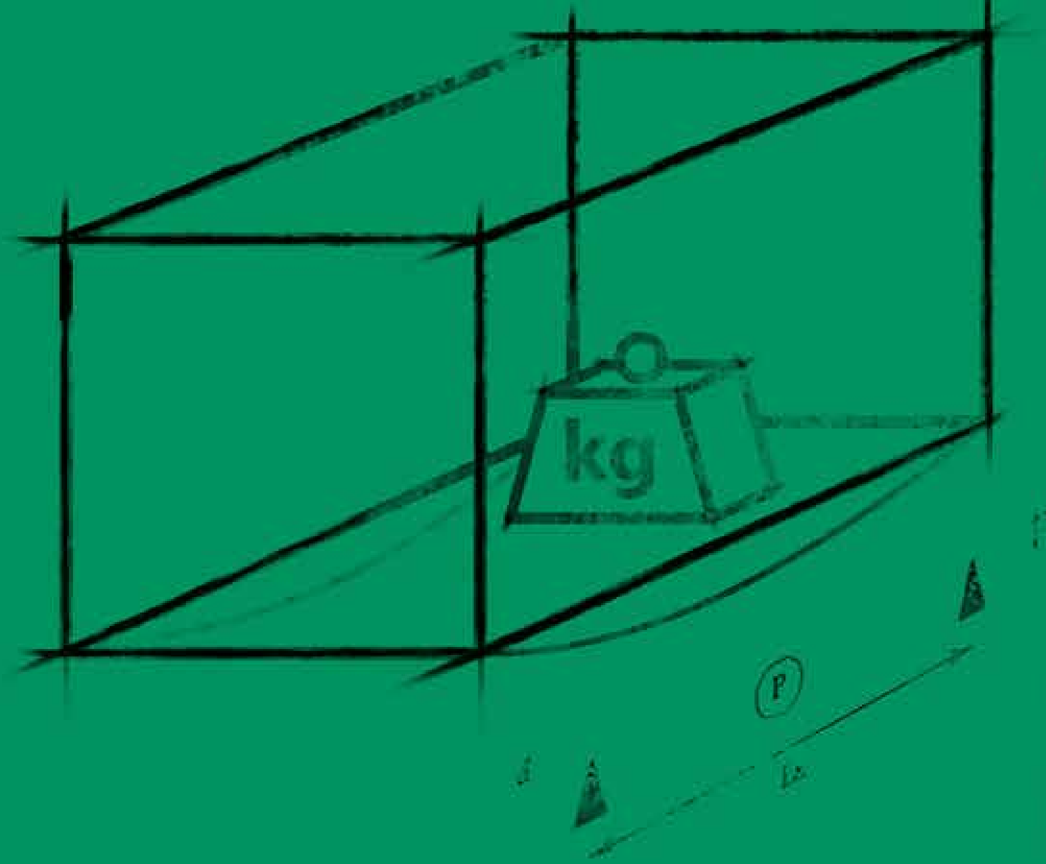

CHAPTER 6

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The U.S. Edition of the CLT Handbook: *cross-laminated timber* combines the work and knowledge of American, Canadian and European specialists. The handbook is based on the original Canadian Edition of the CLT Handbook: *cross-laminated timber*, that was developed using a series of reports initially prepared by FPInnovations and collaborators to support the introduction of CLT in the North American market. A multi-disciplinary team revised, updated and implemented their know-how and technologies to adapt this document to U.S. standards.

The publication of this handbook was made possible with the special collaboration of the following partners:

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The information contained in this Work represents current research results and technical information made available from many sources, including researchers, manufacturers, and design professionals. The information has been reviewed by professionals in wood design including professors, design engineers and architects, and wood product manufacturers. While every reasonable effort has been made to insure the accuracy of the information presented, and special effort has been made to assure that the information reflects the state-of-the-art, none of the above-mentioned parties make any warranty, expressed or implied, or assume any legal liability or responsibility for the use, application of, and/or reference to opinions, findings, conclusions, or recommendations included in this published work, nor assume any responsibility for the accuracy or completeness of the information or its fitness for any particular purpose.

This published Work is designed to provide accurate, authoritative information but is not intended to provide professional advice. It is the responsibility of users to exercise professional knowledge and judgment in the use of the information.

ABSTRACT

Cross-laminated timber (CLT) products are used as load-carrying slab and wall elements in structural systems, thus load duration and creep behavior are critical characteristics that must be addressed in structural design. Given its lay-up construction with orthogonal arrangement of layers bonded with structural adhesive, CLT is more prone to time-dependent deformations under load (creep) than other engineered wood products such as structural glued-laminated timber.

Time dependent behavior of structural wood products is addressed in design standards by load duration factors that adjust design properties. Since CLT has been recently introduced into the North American market, the current design standards and building codes do not specify load duration and creep adjustment factors for CLT. Until this can be rectified, an approach is proposed in this Chapter for adopters of CLT systems in the United States. This includes not only load duration and service factors, but also an approach to accounting for creep in CLT structural elements.

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1

INTRODUCTION

This Chapter aims at describing how the duration of load[1] and creep[2] effects of wood are taken into account in design of wood structures, when the design is carried out in accordance with the current design standards for wood construction in the United States. Since cross-laminated timber (CLT) is not covered by the National Design Specification for Wood Construction (NDS), the intent of this Chapter is to recommend an approach that accounts for the duration of load and creep effects in the design of CLT.

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[1] Load duration is defined as the period of continuous application of a given load or a series of periods of intermittent applications of the same load type (IBC® Commentary, 2009).

[2] Creep is defined as a slow deformation of a material in time under constant loading.

2

DURATION OF LOAD AND CREEP EFFECTS IN THE UNITED STATES CODES AND STANDARDS

Current duration of load factors for wood were determined many years ago based on the work that led to the development of the Madison Curve[3]. Some tests conducted in the development of this curve lasted as long as ten years; so repeating this work to develop a similar curve for CLT is not practical.

Furthermore, the most recent product standard developed for the evaluation of duration of load and creep effects (ASTM D6815, 2009) is a pass/fail procedure meant to verify that the current creep/duration of load adjustments are appropriate for new products and was developed for the evaluation of engineered wood products. The background information on the development of ASTM D6815 is described in its commentary and in the literature (Karacabeyli, 2001). This standard, at the moment, does not provide a method for calculation of duration of load or creep factors, and therefore it would not be practical to carry out ASTM D6815 tests on full-size CLT specimens as it cannot lead to duration of load and creep factors specific to CLT. The National Design Specification for Wood Construction, ANSI/AWC NDS-2012 (AWC, 2012) takes into account duration of load (that accounts for the dependency of wood on duration of applied load); however, it does not include the effect of moisture on the duration of applied load. It should be noted that CLT products manufactured in accordance with ANSI/APA PRG 320 standard (ANSI, 2011), as discussed in Chapter 2 *Cross-laminated timber manufacturing*, are limited to the use in dry service conditions (i.e., moisture content of less than 16%).

2.1 Load Duration Factors in ANSI/AWC NDS-2012

A load duration factor, C_D, is specified in Clause 2.3.2 of ANSI/AWC NDS-2012 for Allowable Stress Design (ASD) for six load categories: permanent, ten years, two months, seven days, ten minutes, and impact loading. The reference design values are given for normal load duration which assumes full design load for a cumulative period of ten years. The load duration factors for ASD are given in Table 1.

---

[3] The Madison Curve shows the predicted relationship between bending strength and duration of load of wood. It is based on load duration tests of small clear specimens (Wood, 1951).

Table 1

Load duration factors for ASD, C_D (Table 2.3.2, ANSI/AWC NDS-2012)

Load Duration	C_D[1]	Typical Design Loads
Permanent	0.9	Dead load
Ten years	1.0	Occupancy live load
Two months	1.15	Snow load
Seven days	1.25	Construction load
Ten minutes	1.6	Wind/earthquake load
Impact [2]	2.0	Impact load

Notes: [1] Load duration factors do not apply to reference modulus of elasticity, E, reference modulus of elasticity for beam and column stability, E_{min}, and reference compression perpendicular to grain design values, $F_{c\perp}$, which are based on a deformation limit.

[2] Load duration factors greater than 1.6 do not apply to structural members pressure-treated with water-borne preservatives, or fire retardant chemicals. The impact load duration factor does not apply to connections.

In the case of Load and Resistance Factor Design (LRFD), design properties are adjusted by the time effect factor, λ, given in Clause 2.3.7 of ANSI/AWC NDS-2012 and shown in Table 2.

Table 2

Time effect factors for LRFD, λ (Table N.3, ANSI/AWC NDS-2012)

Load Combination [2]	Time Effect Factors, λ
1.4D	0.6
1.2D+1.6L+0.5(L_r or S or R)	0.7 when L is from storage
	0.8 when L is from occupancy
	1.25 when L is from impact[1]
1.2D+1.6(L_r or S or R)+(L or 0.8W)	0.8
1.2D+1.0W+L+0.5(L_r or S or R)	1.0
1.2D+1.0E+L+0.2S	1.0
0.9D+1.0W	1.0
0.9D+1.0E	1.0

Notes:

[1] Time effect factors, λ, greater than 1.0 shall not apply to connections or to structural members pressure-treated with water-borne preservatives (see Reference 30 in ANSI/AWC NDS-2012) or fire retardant chemicals.

[2] Load combinations and load factors consistent with ASCE/SEI 7-10 (ASCE, 2010) are listed for ease of reference. Nominal loads shall be in accordance with N.1.2 of ANSI/AWC NDS-2012. D = dead load; L = live load; L_r = roof live load; S = snow load; R = rain load; W = wind load; and E = earthquake load.

Design properties adjusted for duration of load are determined by multiplication of ASD reference design values by the load duration factors given in Table 1 and LRFD reference design values by time effect factors given in Table 2. The load duration factors, as indicated above, are used to adjust design values of solid sawn lumber, engineered wood products, and connections.

2.2 Total Deflection under Long-term Loading in ANSI/AWC NDS-2012

Clause 3.5.2 of ANSI/AWC NDS-2012 provides an equation for calculating the total deflection under long-term loading when the design is governed by deflection and this must be limited:

$$\Delta_T = K_{cr}\,\Delta_{LT} + \Delta_{ST} \qquad [1]$$

where,

K_{cr} = time dependent deformation (creep) factor

= 1.5 for seasoned lumber, structural glued-laminated timber, prefabricated wood I-joists, or structural composite lumber used in dry service conditions.

= 2.0 for structural glued-laminated timber used in wet service conditions (i.e., where moisture content in service is 16% or higher)

= 2.0 for wood structural panels used in dry service conditions (i.e., where moisture content in service is less than 16%)

= 2.0 for unseasoned lumber or for seasoned lumber used in wet service conditions (i.e., where moisture content in service exceeds 19% for an extended period of time)

Δ_{LT} = immediate deflection due to the long-term component of the design load

Δ_{ST} = deflection due to the short-term or normal component of the design load

2.3 Temperature Factors in ANSI/AWC NDS-2012

ANSI/AWC NDS-2012 provides temperature factors, C_t, for structural members expected to be exposed to sustained elevated temperatures up to 150°F (65.5°C) in service[4]. Reference design values for specific loading conditions and in-service moisture conditions are multiplied by the appropriate temperature factors, which are shown in Table 3.

---

[4] The temperature effect is reversible up to 150°F (65.5°C), i.e., wood regains its strength after it is cooled to its normal temperature; prolonged exposure to temperatures beyond 150°F (65.5°C) can cause irreversible damage to the wood structure and permanent loss of strength. The magnitude of the temperature effect is dependent on the moisture content of the wood, which varies according to the in-service moisture conditions.

Table 3

Temperature factors, C_t (from Table 2.3.3 in ANSI/AWC NDS-2012)

Reference Design Value[1]	In-service Moisture Conditions[2]	Temperature Factors, C_t		
		T≤100°F (T≤37.7°C)	100°F<T≤125°F (37.7°C<T≤51.6°C)	125°F<T≤150°F (51.6°C<T≤65.5°C)
F_t, E, E_{min}	Wet or Dry	1.0	0.9	0.9
F_b, F_v, F_c, and $F_{c\perp}$	Dry	1.0	0.8	0.7
	Wet	1.0	0.7	0.5

Notes:

[1] F_b = reference bending design value, psi; F_t = reference tension design value parallel to grain, psi; F_v = reference shear design value parallel to grain (horizontal shear), psi; $F_{c\perp}$ = reference compression design value perpendicular to grain, psi; F_c = reference compression design value parallel to grain, psi; E = reference modulus of elasticity, psi; E_{min} = reference modulus of elasticity for beam stability and column stability calculations, psi.

[2] Wet and dry service conditions for structural glued-laminated timber and wood structural panels are described in section 2.4.

2.4 Service Condition Factors in ANSI/AWC NDS-2012

ANSI/AWC NDS-2012 defines service conditions for various wood products. In the case of structural glued-laminated timber and plywood, dry service conditions apply when the average equilibrium moisture content in service is less than 16%, as in most protected structures. To deal with service conditions other than dry (i.e., when average equilibrium moisture content in service is 16% or greater), ANSI/AWC NDS-2012 provides wet service factors, C_M. Reference design values for specific loading conditions are multiplied by the appropriate wet service factors. Service adjustment factors for structural glued-laminated timber are shown in Table 4.

Table 4

Service adjustment factors for structural glued-laminated timber (from Table 5.3.1 and Table 5A/5B/5C/5D in ANSI/AWC NDS-2012)

Service Adjustment Factors (for ASD and LRFD), psi			Structural Glued-laminated Timber	
			Dry Service Factor	Wet Service Factor, C_M
Bending [1]	F_b	x	1.00	0.8
Tension [2]	F_t	x	1.00	0.8
Shear [3]	F_v	x	1.00	0.875
Compression perpendicular to grain [4]	$F_{c\perp}$	x	1.00	0.53
Compression parallel to grain [5]	F_c	x	1.00	0.73
Radial tension perpendicular to grain [6]	F_{rt}	x	1.00	0.875
Modulus of elasticity [7]	E	x	1.00	0.833
Modulus of elasticity (beam/column stability) [8]	E_{min}	x	1.00	0.833

Notes:

[1] F_b = reference bending design value, psi; [2] F_t = reference tension design value parallel to grain, psi; [3] F_v = reference shear design value parallel to grain (horizontal shear), psi; [4] $F_{c\perp}$ = reference compression design value perpendicular to grain, psi; [5] F_c = reference compression design value parallel to grain, psi; [6] F_{rt} = reference radial tension design value perpendicular to grain, psi; [7] E = reference modulus of elasticity, psi; [8] E_{min} = reference modulus of elasticity for beam stability and column stability calculations, psi.

For wood structural panels used in service conditions other than dry (i.e., when average equilibrium moisture content in service is 16% or greater), wet service factors from an approved source, such as *Panel Design Specification* published by APA – The Engineered Wood Association, are used.

3

RECOMMENDED APPROACH FOR DURATION OF LOAD AND CREEP EFFECTS OF CLT IN THE UNITED STATES

CLT is not among the wood products covered in the ANSI/AWC NDS-2012, and consequently there are no load duration and service condition factors specified for this product. Until CLT is included in the NDS, this section provides proposed load duration and service factors as well as an approach to account for creep in CLT structural elements.

1) ***Load Duration Factor***: It is recommended to use the load duration factor, C_D, for ASD as specified in Table 1 (from Table 2.3.2 of ANSI/AWC NDS-2012), or the time effect factor, λ, for LRFD as specified in Table 2 (from Table N.3 of ANSI/AWC NDS-2012).

2) ***Temperature Factor***: It is recommended to use the temperature factor, C_t, given for structural glued-laminated timber in dry service conditions at temperatures up to 150°F (65.5°C) in Table 3 (from Table 2.3.3 in ANSI/AWC NDS-2012).

3) ***Service Condition Factor***: For dry service conditions (i.e., moisture content of less than 16%), use the service condition factor of 1.0 (similar to the service adjustment factors for structural glued-laminated timber given in Table 4). Consult with the CLT manufacturer for other than dry service conditions.

4) ***Creep Factor***: The current factor specified in ANSI/AWC NDS-2012 does not account for creep that may occur in CLT. Therefore, the time dependent deformation (creep) factor $K_{cr} = 2.0$ is recommended for dry service conditions. A creep factor $K_{cr} = 2.5$ is suggested for wet service conditions, although it is strongly recommended to consult with the CLT manufacturer before using any CLT product in conditions other than dry service.

The load duration factors specified in ANSI/AWC NDS-2012 may not conservatively account for shear perpendicular to the grain (rolling shear) effects; however, the design of CLT used as floor and roof elements is usually governed by deflection. The proposed time dependent deformation (creep) factor is based on 30%-40% higher creep values for CLT compared to structural glued-laminated timber for one year of sustained loading, as reported by Jöbstl and Schickhofer (2007). The factors for duration of load and creep in the European codes, and the approach taken for the duration of load and creep effects of CLT are described in the Appendix.

The designer is advised to check the elastic deflection and permanent deformation for CLT slab elements as to not exceed the total load deflection limit in the code (Table 1604.3 of the IBC (ICC, 2012)).

Verification of shear and bending out-of-plane strengths is explained in detail in Chapter 3, *Structural design of cross-laminated timber elements*.

The designer is advised to check the maximum floor vibrations for CLT slab elements. A design method for controlling vibrations in CLT floors is provided in Chapter 7, *Vibration performance of cross-laminated timber floors*.

4

MODIFICATION FACTORS FOR CONNECTIONS USED IN CLT BUILDINGS

Load duration and time-dependent slip behavior of connections also affect the performance of a CLT system. Clause 10.3.2 in ANSI/AWC NDS-2012 specifies for ASD the same load duration factors, C_D, for mechanical connections as shown in Table 1 with the exception of impact load duration, while clause 10.3.9 specifies the time effect factors in Table 2 for LRFD. Temperature factors, C_t, and wet service condition factors, C_M, for various fastener types are tabulated in Tables 10.3.4 and 10.3.3, respectively, in the ANSI/AWC NDS-2012 standard. Additional information on connections with CLT is given in Chapter 5, *Connections in cross-laminated timber buildings*.

5

PRODUCT-SPECIFIC PARAMETERS THAT MAY AFFECT DURATION OF LOAD AND CREEP EFFECTS OF CLT

5.1 Adhesives

A structural adhesive is not expected to creep in service. The U.S. standards for evaluation of adhesives for structural application have built-in tests for assessing creep under various loads and service conditions. The ANSI/APA PRG 320 standard specifies that adhesives for CLT manufacturing have to pass the minimum requirements of AITC 405, Standard for Adhesives for Use in Structural Glued Laminated Timber (AITC 405, 2008). The AITC 405 standard specifies the test methods of ASTM D 2559, Standard Specification for Adhesives for Bonded Structural Wood Products for Use Under Exterior Exposure Conditions (ASTM, 2012) and CSA O112.9, Evaluation of adhesives for structural wood products (exterior exposure) (CSA, 2004), for evaluation of creep resistance of adhesive bonds. Adhesives passing the minimum requirements of the required standards would show insignificant creep in the bond line relative to the creep that occurs in CLT products due to the orientation of cross laminations.

5.2 Edge-gluing and Width-to-thickness Ratio

CLT products without edge-glued laminations may have lower load-carrying capacities than those with edge-glued laminations due to lower rolling shear modulus. However, no research results have been published to show any correlation between rolling shear modulus of edge-glued and non-edge-glued laminations and its effect on load carrying capacity of the CLT element.

Parameters affecting rolling shear properties include: lamination width, direction of annual rings in boards, earlywood to latewood ratios, adhesive type, panel pressure during manufacturing, and type of loading. A true value of rolling shear modulus is difficult to obtain due to very low shear deflections measured during the tests, which makes the calculation of rolling shear modulus very sensitive to experimental error. In Europe, a rolling shear modulus of 7252 psi (50 MPa) is often used for CLT design; this value was obtained for spruce with an oven-dry density of 29 lb./ft.^{3} (460 kg/m^3) (Aicher and Dill-Langer, 2000; Aicher *et al*., 2001). Typically, rolling shear modulus for spruce ranges from 5802 psi (40 MPa) to 11603 psi (80 MPa) (Fellmoser and Blass, 2004).

Preliminary observation suggests a decrease in rolling shear modulus with decreasing width-to-thickness ratio of boards in the cross layer. A minimum width-to-thickness ratio of 4 is suggested for lumber to ensure good contact during pressing and adequate rolling shear strength (Schickhofer *et al*., 2009; Schickhofer, 2010). The draft European standard for CLT recommends further verification through testing when the minimum width-to-thickness ratio of lumber is less than 4 (CEN, 2012). For these reasons, ANSI/APA PRG 320 requires that rolling shear strength and modulus be verified by testing when using cross laminations with a width-to-thickness ratio of less than 3.5. Research is ongoing to develop appropriate testing methods for assessing rolling shear strength of CLT, and to quantify the width-to-thickness effect.

5.3 Stress Release Grooves

CLT containing stress release grooves is beyond the scope of this CLT Handbook and the manufacturing and design provisions given in Chapter 2, *Cross-laminated timber manufacturing*, and Chapter 3, *Structural design of cross-laminated timber elements*, respectively, do not cover such products. Some manufacturers in Europe mill release grooves into lumber in cross laminations to minimize the effect of cupping. The depth of grooves may take up to 90% of the lumber thickness and may have a maximum width of 0.16 in. (4 mm) (CEN, 2012). CLT products manufactured with release grooves are likely to have lower load-carrying capacities than those without release grooves due to the lower rolling shear modulus of cross laminations caused by the release grooves. Failure of CLT loaded in bending is typically initiated in the cross layers by rotation of the cross layers and “rolling” of the earlywood zones in lumber (Augustin, 2008). The cross section is significantly reduced at the grooves and prone to failure under high loads generating narrower strips of lumber that are further likely to “roll” under load, leading to high deformations and, ultimately, failure. Since the release grooves are considered unbonded edges, it is recommended that rolling shear strength and modulus be verified by testing when using CLT containing stress release grooves.

5.4 Nail or Wooden Dowel Fastened CLT Products

Mechanically fastened CLT (i.e., not adhesively bonded) is beyond the scope of this CLT Handbook and the manufacturing and design provisions given in Chapter 2, *Cross-laminated timber manufacturing*, and Chapter 3, *Structural design of cross-laminated timber elements*, respectively, do not cover such products. In Europe, some manufacturers are using aluminum nails or wooden dowels to vertically connect wood layers in CLT. Some of these CLT products are not glued-laminated, and may deflect and creep significantly more than adhesively-bonded CLT. Researchers at the University of British Columbia have found up to four times larger deflections for nailed CLT specimens compared to glued CLT specimens for the same specimen thickness (Chen and Lam, 2008). The deflection range was due to different nailing schedules of the CLT layers. Some of these products may be more suitable for wall applications but the load duration and creep factors recommended in this document are not applicable to mechanically fastened CLT products.

6

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APPENDIX A

The approach taken in this Chapter to account for the duration of load and creep effects of CLT makes use of the research carried out in Europe and the approach adopted to account for similar effects in the European codes and standards, which are described below.

A1 Duration of Load and Creep Effects in European Codes and Standards

The current European approach takes into account the duration of load and creep effects by introducing load duration classes associated with accumulated duration of load. The load duration and creep factors take into account duration of load classes and service classes, and they are product specific. The main factors affecting creep of wood-based products include the magnitude, type and duration of load, moisture content and temperature. Interactions occur among all factors, but only the combined effects of load duration and moisture content are taken into account in the design rules specified in EN 1995-1-1: Eurocode 5 – Design of Timber Structures (CEN, 2004), which provides load duration classes and modification factors for service classes that are used in the design of structures. Load duration classes are shown in Table 5, while service classes are shown in Table 6.

Table 5
Load duration classes (Table 2.1, EN 1995-1-1)

Load Duration Class	Accumulated Duration of Load
Permanent	> 10 years
Long term[†]	6 months - 10 years
Medium term	1 week - 6 months
Short term	< 1 week
Instantaneous	N/A

Note: [†]Long term load duration in ANSI/AWC NDS-2012 is 10 years, medium term is 2 months, short term is 7 days, and instantaneous is impact load duration. Ten-minute load duration is specified in ANSI/AWC NDS-2012 for wind/earthquake loads.

Table 6
Service classes (Clause 2.3.1.3, EN 1995-1-1)

Service Class	Climatic Condition
Service class 1	Moisture content (MC) of material at 68°F (20°C) and > 65% relative humidity (RH) for a few weeks per year (softwood timber MC < 12%; panels MC < 8%)
Service class 2	Moisture content (MC) of material at 68°F (20°C) and > 85% relative humidity (RH) for a few weeks per year (softwood timber MC < 20%; panels MC < 15%)
Service class 3	Condition leading to higher MC than service class 2 (timber MC > 20%; panels MC > 15%)

Note: ANSI/AWC NDS-2012 defines dry service conditions for lumber as climatic conditions at which MC in use is maximum 19% regardless of the MC at the time of manufacture. Similarly, dry service conditions for wood structural panels are climatic conditions at which MC in use is less than 16%. Wet service conditions correspond to all conditions other than dry.

A1.1 Strength Modification Factors in EN 1995-1-1

Product-specific strength modification factors, k_{mod}, for service classes and load duration classes are given in Table 7. Note that design strength and capacity values are based on tests to failure in 5±2 minutes, and they are similar for structural glued-laminated timber and plywood.

Table 7

Strength modification factor, k_{mod} (Table 3.1, EN 1995-1-1)

Material/Load Duration Class	Service Class 1	Service Class 2	Service Class 3
Structural Glued-laminated Timber			
Permanent	0.60	0.60	0.50
Long term	0.70	0.70	0.55
Medium term	0.80	0.80	0.65
Short term	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90
Plywood [1]			
Permanent	0.60	0.60	0.50
Long term	0.70	0.70	0.55
Medium term	0.80	0.80	0.65
Short term	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90

Notes:

[1] Plywood classified in accordance to Part 1, Part 2 and Part 3 of EN 636 may be used under Service Class 1; plywood classified in accordance to Part 2 and Part 3 of EN 636 may be used under Service Class 2; and plywood classified in accordance to Part 3 of EN 636 may be used under Service Class 3. Additional information about the three plywood categories is given in Table 8.

A1.2 Deformation Modification Factors in EN 1995-1-1

Deformation or creep factor, k_{def}, takes into account creep deformation for the relevant service classes, and is shown in Table 8.

Table 8

Deformation modification factor, k_{def} (Table 3.2, EN 1995-1-1)

Material (Standard)	Service Class 1	Service Class 2	Service Class 3
Solid timber[1] (EN 14081-1)	0.60	0.80	2.00
Structural glued-laminated timber (EN 14080)	0.60	0.80	2.00
Plywood (EN 636)[2]			
Part 1	0.80	-	-
Part 2	0.80	1.00	-
Part 3	0.80	1.00	2.50

Notes:

[1] k_{def} is to be increased by 1.00 for timber near saturation point which is likely to dry out under load;

[2] The 1997 edition of EN 636 classified plywood in the following three categories:

Part 1: Plywood manufactured for use in DRY conditions = interior applications with no risk of wetting, defined in hazard class 1, with a moisture content (MC) corresponding to environmental conditions of 68°F (20°C) and 65% RH (12% MC or less).

Part 2: Plywood manufactured for use in HUMID conditions = protected exterior applications as defined in hazard class 2, with a MC corresponding to environmental conditions of 68°F (20°C) and 90% RH (20% MC or less).

Part 3: Plywood manufactured for use in EXTERIOR conditions = unprotected external applications, as defined in hazard class 3, where the MC will frequently be above 20%.

The latest version of EN 636 (2003) integrates the three separate parts for plywood for use in dry conditions (EN 636-1:1997), humid conditions (EN 636-2:1997), and exterior conditions (EN 636-3:1997), and supersedes the 1997 editions.

A2 European Approach for Duration of Load and Creep Effects of CLT

Material properties including duration of load and creep factors for CLT are not specified in Eurocode 5 because of the proprietary nature of these products in Europe. However, CLT is covered in some national building codes such as DIN 1052, *Design of Timber Structures in Germany* (Beuth Verlag GmbH, 2008) and SIA 265, *Timber Structures Section of the Swiss Building Code* (SVN, 2003). Engineers in Europe use allowable design values indicated in product catalogues which are made available by the CLT manufacturers to design CLT structures, and obtain special approvals from local building officials.

Research conducted at Graz University of Technology in Austria concluded that long-term behavior of CLT products is more likely comparable with that of other cross-laminated wood-based products (such as plywood) as opposed to products laminated unidirectionally (such as structural glued-laminated timber) (Jöbstl and Schickhofer, 2007). The authors reported 30%-40% larger creep values for CLT compared to structural glued-laminated timber after one year loading in bending, which is attributed to crosswise layers in CLT. One year constant load duration can be assumed sufficient to account for the cumulative damage effects due to occupancy and snow loads. Using the deformation factor obtained for 5-layer CLT, the authors derived the deformation factors for CLT products ranging from 3 to 19 layers, and recommended using the deformation factor for plywood for CLT with more than 9 layers, and increase the deformation factor for plywood by 10% for CLT with 7 layers or less. A 10% increase in k_{def} factors for plywood (Table 8) is reflected in the calculation of k_{def} factors for CLT (Table 9) to account for the differences between CLT and structural glued-laminated timber test results obtained by Jöbstl and Schickhofer (2007). For long-term loads, however, a further increase of k_{def} or reduction of deformation limits is recommended.

Table 9

Deformation modification factor, k_{def}, adjusted to CLT (based on recommendations of Jöbstl and Schickhofer, 2007)

Material (Standard)	Service Class 1	Service Class 2	Service Class 3
CLT	0.90	1.10	N/A

In Eurocode 5, the final deformation is calculated for the quasi-permanent[5] combination of actions. Assuming a linear relationship between the loads and the corresponding deformations, the final deformation (u_{fin}) may be calculated as a sum of the final deformation due to permanent loads ($u_{fin,P}$), the final deformation due to the main live loads ($u_{fin,Q1}$), and the final deformation due to accompanying live loads ($u_{fin,Qi}$) (Clause 2.2.3(5) of EN 1995-1-1).

$u_{fin,P} = u_{inst,P}\,(1 + k_{def})$ -- for permanent loads, P [2]

$u_{fin,Q,1} = u_{inst,Q,1}\,(1 + \psi_{2,1}k_{def})$ -- for main live loads, Q_1 [3]

$u_{fin,Q,i} = u_{inst,Q,i}\,(\psi_{0,i} + \psi_{2,i}k_{def})$ -- for accompanying live loads, Q_i (i>1) [4]

$u_{inst,P}$, $u_{inst,Q,1}$, $u_{inst,Q,i}$ = instantaneous deformations for loads P, Q_1, Q_i, respectively

where,

$\psi_{2,1}$, $\psi_{2,i}$ = factors for the quasi-permanent value of live loads;

$\psi_{0,i}$ = factors for the combination value of live loads;

k_{def} = deformation factor.

The ψ factors given in EN 1990 (CEN, 2002a) are shown in Table 10.

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[5] Quasi-permanent combination is used mainly to take into account long-term effects.

Table 10

Recommended values of ψ factors for buildings (from Table A.1.1 in EN 1990)

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1[1])			
Category A: domestic, residential areas	0.7	0.5	0.3
Category B: office areas	0.7	0.5	0.3
Category C: congregation areas	0.7	0.7	0.6
Category D: shopping areas	0.7	0.7	0.6
Category E: storage areas	1.0	0.9	0.8
Category F: traffic area, vehicle weight ≤ 6744 lb. (30 kN)	0.7	0.7	0.6
Category G: traffic area, 6744 lb. (30 kN) ≤ vehicle weight ≤ 35970 lb. (160 kN)	0.7	0.5	0.3
Category H: roofs	0.0	0.0	0.0
Snow loads on buildings (see EN 1991-1-3[2])*			
Finland, Iceland, Norway, Sweden	0.7	0.5	0.2
Remainder of CEN Member States, for sites located at altitude H > 3281 ft. (1000 m) a.s.1.	0.7	0.5	0.2
Remainder of CEN Member States, for sites located at altitude H ≤ 3281 ft. (1000 m) a.s.1.	0.5	0.2	0.0
Wind loads on buildings (see EN 1991-1-4[3])	0.6	0.2	0.0
Temperature (non-fire) in buildings (see EN 1991-1-5[4])	0.6	0.5	0.0

Notes: The ψ values may be set by the National annex.

* For countries other than Finland, Iceland, Norway and Sweden, see relevant local conditions.

[1] Eurocode 1, Part 1-1 (CEN, 2002b)

[2] Eurocode 1, Part 1-3 (CEN, 2002c)

[3] Eurocode 1, Part 1-4 (CEN, 2002d)

[4] Eurocode 1, Part 1-5 (CEN, 2002e)

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