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Overview of the Protective Design Center Technical Report (PDC-TR) 18-02:

Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading

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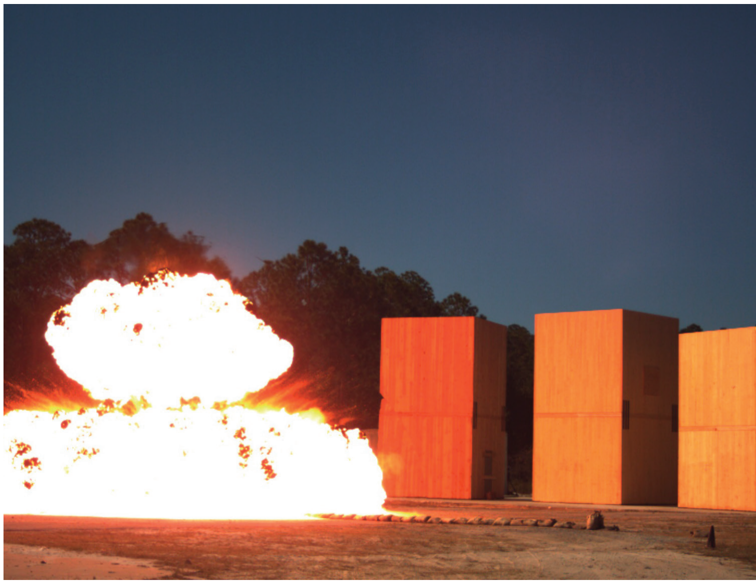
Buildings constructed for the U.S. Department of Defense (DoD) often have to meet blast-resistance requirements to mitigate the potential effects of terrorism. Terrorism is also a growing threat for civilian buildings (e.g., iconic structures, corporate headquarters, etc.), necessitating more building designers to incorporate blast resistance into their designs. The emergence of mass timber construction, and cross-laminated timber (CLT) in particular, offers a sustainable building material alternative that can also meet blast-resistance criteria in many circumstances.

The U.S. government and designers alike are motivated by the advantages inherent in CLT construction, which include:

- ***Sustainability*** – CLT has a light carbon footprint and performs well from an energy-efficiency standpoint.
- ***Conservation*** – CLT can be made from smaller diameter trees and trees impacted by insects and disease, which can contribute to forest health by incentivizing forest thinning and reducing the risk of wildfire.
- ***Job creation*** – The manufacture of CLT requires skilled workers, which creates well-paying jobs that strengthen rural economies.
- ***Strength*** – The solid, built-up nature of CLT allows for inherent strength.
- ***Constructability*** – CLT panels can be fabricated off-site and rapidly joined using easy-to-install screw-type fasteners.

Two U.S. Forest Service-sponsored efforts over the last few years have demonstrated the ability of CLT construction to resist blast loads in a controlled and predictable fashion. Based on this testing, Protective Design Center Technical Report (PDC-TR) 18-02 *Analysis Guidance for Cross-Laminated Timber Construction Exposed to Airblast Loading* was publicly-released to enable engineers trained in structural dynamics to analyze and design CLT structures for blast loads. This PDC-TR can be accessed for free at https://www.nwo.usace.army.mil/pdc/home/. The following narrative outlines the content of this PDC-TR and how it can be utilized.



The Purpose of PDC-TR 18-02

Single degree-of-freedom (SDOF) dynamic analysis is commonly used to analyze structural components for the intense overpressure generated by explosions. This type of analysis computes the maximum lateral displacement of the component for a given blast load, which can then be compared with a displacement-based "response limit." For each type of component, the response limits vary based on the level of damage the component is permitted to have.

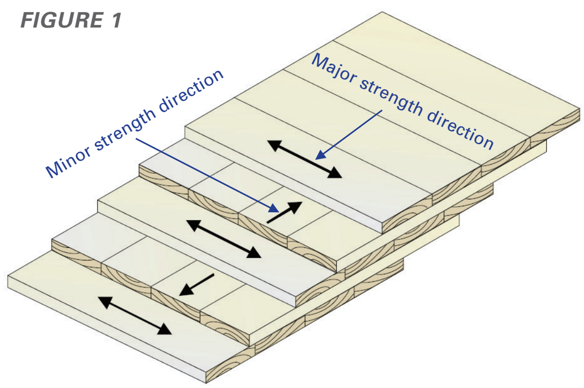
Response limits generally take the form of a displacement ductility ratio, μ, and/or an end support rotation, θ. For the design of buildings required to resist blast loading, PDC-TR 06-08 defines these ductility ratios and support rotations for various structural components. CLT is not currently included as a structural component in this document. Thus, a primary purpose of PDC-TR 18-02 is to define these response limits, communicate analysis assumptions and procedures, and discuss how to interpret analytical results to facilitate the proper implementation of these response limits.

About CLT

CLT is an engineered wood panel product consisting of multiple layers (i.e., plies) of dimension lumber or structural composite lumber aligned edge-to-edge, stacked orthogonally, and bonded on their wide faces with structural adhesives. The orientation of the outermost panel plies is termed the "major strength direction" and that of the crosswise panel plies is termed the "minor strength direction" (see Figure 1). Two grade classifications exist for CLT panels certified in accordance with ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber – (1) "E" or engineered, which utilizes machine stress-rated (MSR) lumber in the major strength direction, and (2) "V" or visually-graded, which utilizes visually-graded lumber in the major strength direction. The specific combination of ply number, ply thickness(es), lumber species, and lumber grade is referred to as the panel's "layup."

Several standards and references are useful when designing CLT structures for blast loads. PRG 320 provides dimensions and tolerances, performance requirements, test methods, quality assurance, and trademarking for CLT panels. Annex A of PRG 320 defines the layups for four "E" grades and three "V" grades and includes allowable stress design (ASD) reference design values based on the Shear Analogy Method for each grade. Manufacturers often create custom grades which are not listed in Annex A but are permitted by meeting the requirements of Section 7.2.1 of PRG 320.

FIGURE 1



Other references of relevance include:

- The 2018 National Design Specification® for Wood Construction (NDS®) defines adjustment factors for CLT panel and connection reference design values.
- The CLT Handbook is a central repository of information related to CLT analysis, design, and construction.
- Section 06 17 19 of the Unified Facilities Guide Specifications (UFGS) serves as the guide specification for the fabrication and erection of CLT panels for walls, floors, roofs, partitions, and all metal shapes and hardware required for their installation.

It should be noted that the blast analysis guidance included in PDC-TR 18-02 is limited by the following assumptions:

- Design loads are derived from far-field explosions associated with terrorism. Close-in and contact loading ranges are outside the scope of PDC-TR 18-02.
- The CLT panel can be idealized with a single analytical degree of freedom; this assumption is generally appropriate for CLT panels exposed to far-field blast loads.
- The compression stress parallel to grain, f_c, resulting from the full-service load is not more than 50 percent of the average design value parallel to grain, F_{dc}. Information on how to compute F_{dc} is included in PDC-TR 18-02. This assumption captures the redundancy in load capacity in CLT and is expected to cover most low and mid-rise buildings.

The Blast Load

Blast loads for far-field detonations are approximated by a set of empirical curve-fits known collectively as the Kingery-Bulmash (K-B) equations. Information on how to generate blast loads using the K-B equations can be found in Chapter 2 of United Facilities Criteria (UFC) 3-340-02, Structures to Resist the Effects of Accidental Explosions. Once the blast load parameters are determined using the K-B equations, a pressure history can directly be developed and imported into Newton's second law of motion.

Blast tests have indicated that CLT panels exposed to blast loads commonly exhibit larger rebound responses than inbound responses. This is common for lighter weight materials displaced elastically. As CLT panels are routinely used as load-bearing walls, it is important that the negative phase of the blast load be considered when analyzing these panels for blast loads. Thus, two blast load cases should be considered for CLT panels exposed to blast loads: (1) positive-phase-only, and (2) positive-plus-negative-phase. The consideration of both cases will help to approximate both inbound and rebound displacements.

CLT Panel Properties That Can be Used in Blast Design

The ASD reference design values for both the major and minor strength directions of selected layups certified by APA – The Engineered Wood Association (APA) in accordance with PRG 320 are included in Appendix A of PDC-TR 18-02. Per Section 10.2 of the NDS, it is important to obtain CLT panel information directly from the manufacturer's literature or code evaluation report when the supplier is known.

Typical wood design for environmental loads relies on 5th percentile values for the purpose of design. When designing structures for blast loads, average, or 50th percentile, material property values are typically used. This approach is significant for two reasons: (1) it serves to minimize the size of the structural component needed to resist the basis-of-design blast loads, and (2) it allows the analyst to

When it was built, Candlewood Suites at Fort Jackson, South Carolina was the largest CLT project in the Eastern U.S., and one of the 10 largest in the country.

Photo: Lendlease

compute realistic boundary condition forces and moments for connection design. As it is common to design structural components to exceed their design "elastic" limit for the purpose of blast design, it is important that the average strength of the component is known to ensure the reaction loads at the connection are not under-designed. Average strength values are not typically the published design values. To obtain average material property values at high strain rates, it is common in the DoD blast design paradigm to apply static and dynamic increase factors.

In the context of CLT, the static increase factor (SIF) is used to transform ASD reference design values reported by the manufacturer into average expected (i.e., 50th percentile) design values assuming normal load duration. The SIF for CLT panels varies depending on the species and grade of the plies in the span direction. Equation (1) of PDC-TR 18-02 indicates the subfactors needed to compute the SIF for CLT panels and Table 1 and Table 2 define the necessary subfactors. From Table 1, it can be seen that the SIF applied to the effective ASD reference flatwise bending moment value, $(F_bS)_{eff}$, varies based on the span direction of concern (i.e., major or minor strength direction), whereas the ASD reference flatwise shear value, V_s, and ASD reference compression value parallel to grain, F_c, do not. In addition to the SIF shown in Equation (1), reference design values should be multiplied by the applicable adjustment factors required by the NDS. Commentary concerning the derivation of CLT SIFs is included in Appendix B of PDC-TR 18-02.

The dynamic increase factor (DIF) is used to increase average expected design values based on normal load duration to account for the strength enhancement effects associated with high strain rates. This factor is similar to the load duration factor, C_D, for impact loading included in the NDS. Commentary concerning the derivation of this DIF is included in Appendix B of PDC-TR 18-02.

The Resistance Function

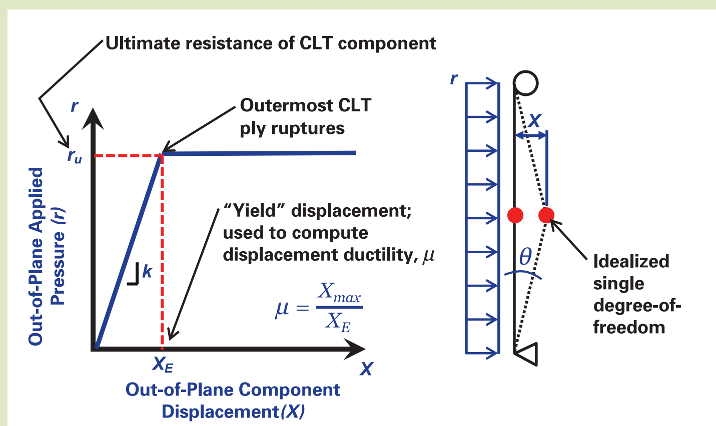
The resistance function is a term used to define the transverse load r (commonly in pressure units) versus displacement, X_e, relationship for the structural component or system being designed. The most basic resistance function that can be used for CLT panels consists of a stiffness and an ultimate resistance (see Figure 2). The resistance function is directly incorporated into Newton's second law of motion as the internal force term.

The stiffness, k, must consider both flexural and shear deformations to arrive at an apparent bending stiffness, $(EI)_{app}$. Equation (2) of PDC-TR 18-02 defines how $(EI)_{app}$ should be computed. All of the terms in this equation are either directly defined by the CLT manufacturer or in Table 3 of PDC-TR 18-02. Once $(EI)_{app}$ is computed, the generic bending deflection equation (i.e., Equation (3) in PDC-TR 18-02) can be used to generate k.

The ultimate resistance, r_u, should be based on the smaller of the flatwise bending and flatwise shear limit states. When exterior walls are also load bearing (i.e., the compressive axial load is greater than 10 percent of the average expected dynamic compression design value parallel to grain, F_{dc}) the effects of axial load should be considered. Equations (4) and (6) of PDC-TR 18-02 are used to compute the flatwise bending moment for non-axial load and axial load conditions, respectively. Additionally, Equation (8) can be used to compute the flatwise shear capacity of a CLT panel. Once the flatwise bending moment and shear capacities are determined, r_u can be computed based on the idealized boundary conditions for one-way spanning members using Table 3-1 of UFC 3-340-02. Although two-way action is inherent in CLT construction, and flexural and shear tests of one-way panel action in both the major and minor strength directions are performed as part of the APA certification process, interaction of the two span directions is not well documented. This is particularly true as it relates to the

FIGURE 2

The Resistance Function



ultimate two-way resistance of the panel and the ensuing post-peak residual capacity. The consideration of two-way action will generally allow for larger panel strengths than can be obtained through one-way action. Thus, common practice when sizing CLT panels, and the assumption in PDC-TR 18-02, is to idealize the panel as a one-way spanning member in either the major or minor strength directions. Further information and standardization of the minor strength direction plies could be used to more directly account for the benefits afforded by two-way action.

Connections

Connection capacity should be designed to exceed the smaller of the demand imposed by the dynamic reaction force or the demand associated with the ultimate resistance, r_u, of the connected CLT panel. Connection capacities should be computed in accordance with the relevant material-specific building code with all relevant strength reduction factors and/or safety factors applied except as modified in Section 11.2 of PDC-TR 18-02.

Connection capacities involving CLT panels should be determined as specified by the NDS, all fastener spacing requirements included in the NDS should be adhered to, and a load duration factor, C_D, of 2.0 may be assumed due to the extremely short duration of the applied blast load. Additional increase factors for lateral and withdrawal values for dowel-type fasteners are specified in PDC-TR 18-02; related commentary can be found in Section C-2.3 of Appendix C.

Response Limits

Response limits for the flatwise response of CLT panels that are compatible with the levels of protection defined in PDC-TR 06-08 are listed in Table 5 of PDC-TR 18-02. The mandated level of protection will dictate the applicable response limit. Per PDC-TR 06-08, the term level of protection is defined as the qualitative degree which an asset (e.g., person, equipment) is protected against injury or damage from a terrorist attack. The response limits reported in Table 5 rely heavily on data and observations obtained from seven blast tests performed on three two-story, single-bay CLT structures at Tyndall Air Force Base (see cover photo).

Based on the post-test photographs, the observed damage in the first-floor front and side wall panels was correlated with the component damage level definitions included in Table 2-4 of PDC-TR 06-08. SDOF dynamic analyses of the first-floor wall panels were then performed using the resistance function, SIFs, and DIF documented in PDC-TR 18-02. The pressure histories recorded during the seven tests were used as the input blast loads. The peak computed displacement ductility for each of these analyses was plotted in the bar chart included as Figure C-2 of PDC-TR 18-02 to correlate displacement ductility to damage level. Based on this process, the response limits in Table 5 were assigned.

An Ending Comment

CLT presents owners and developers with a new building material alternative in civic and government market sectors where steel and concrete have traditionally been used to mitigate hazards associated with blast loads. CLT systems add further value due to their sustainability and light carbon footprint, ability to be shop-fabricated, and speed of installation. By leveraging the Forest Service-funded testing and analysis guidance prescribed in PDC-TR 18-02, an engineer can collaborate with architects to facilitate the use of CLT by ensuring that specified panels can resist the requisite blast loads. The PDC-TR defines how an engineer can determine expected material properties for use in analysis, construct a resistance function appropriate for CLT panels, design connections for the panels, and assess the results of SDOF analyses using response limits documented in PDC-TR 18-02. Additionally, Appendix D of PDC-TR 18-02 includes an example problem that illustrates how an appropriate resistance function for a CLT panel can be constructed.

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