



MODULE FOR ANALYSIS AND CAPACITY-BASED DESIGN OF BRACED TIMBER FRAMES

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ABSTRACT: The National Building Code of Canada (NBCC) specifies values for the ductility-related force modification factor (R_d) for different seismic force resisting systems (SFRSs), which reflects their ability to dissipate energy during a seismic event. For braced timber frames (BTF), NBCC 2020 recognizes two ductility categories: braced frames with moderate and limited ductility, which are assigned an R_d value of 2.0 and 1.5, respectively. However, these values were primarily based on engineering judgment, qualitative comparisons, and experience rather than rigorous analysis using a recognized procedure. Additionally, the Canadian Standard for Engineering Design in Wood, CSA O86, needs to provide specific guidance on how to achieve these two ductility levels. To address this gap, the University of Alberta and FPInnovations are conducting an extensive study to develop specific design provisions for BTFs, including detailed procedures to achieve performance requirements for each level of ductility. This paper represents the first research stage, which involves developing software to analyse and design a range of archetype BTFs using capacity-based design principles.

KEYWORDS: Braced Timber Frame (BTF), Ductile End Brace Connections, Seismic Force Resisting System (SFRS), ductility-related force modification factors (R_d), ductile and moderately ductile connections.

1 INTRODUCTION

The National Building Code of Canada (NBCC) [1] specifies ductility-related force modification factors (R_d) and over-strength-related force modification factors (R_o) for different seismic force-resisting systems (SFRS) to account for a structure's ability to dissipate energy through inelastic behaviour and its dependable reserve strength, respectively. The NBCC 2020 considers Braced Timber Frames (BTFs) with two levels of ductility performance: moderate and limited ductility. The NBCC specifies values of 2.0 and 1.5 for R_d and R_o , respectively, for moderately ductile BTFs. The corresponding values for BTFs with limited ductility are 1.5 and 1.5 [1]. These recommended values were primarily based on engineering judgment, qualitative comparisons, and experience rather than rigorous analysis using a recognized procedure. In addition, no specific guidance is provided in CSA O86 [2] on achieving these ductility levels in terms of end brace connection details as the primary source of ductile behaviour in BTFs. Also, there is no specific design methodology and corresponding tool to design such frames to achieve the desired ductility levels. This project aims to contribute to developing

seismic design provisions for BTFs that can be incorporated into the next edition of CSA O86, specifically provisions to achieve the stated R_d factors in NBCC.

2 METHODOLOGY

To achieve the project goals, the technical guide NRC-CONST-56478E published by Construction Canadian Construction Materials Centre (CCMC), National Research Council of Canada (NRCC), herein referred to as CCMC guideline, is used as the primary reference [3]. This guideline is a simplified version of the FEMA P695 guideline [4]. The procedure requires the study of various archetypes with different attributes that may affect the seismic performance of a building, such as storey heights, number of floors, number of bays, types of dowel-type connections, and earthquake intensities. The nonlinear time history analysis (NLTHA) approach at 100% and 200% of the Uniform Hazard Spectrum (UHS) is suggested to investigate whether the performance criteria are met for the designed archetypes [3]. To facilitate the required tasks, a computer platform is developed with the two modules shown in Figure 1. The first module is a BTF

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linear analysis and capacity-based design module with an in-house developed analysis engine that can mass produce archetype models and the hysteresis loops of selected dowel-type connections necessary for performing NLTHA. These archetypes will be analysed using the OpenSeesPy program [5] and post-processed within module 2 to evaluate their responses to selected seismic motions, scaled according to NBCC [1]. As highlighted in Figure 2, this paper focuses on developing module 1 as a stand-alone software to create the necessary archetype buildings and hysteresis loops of selected dowel-type connections for performing NLTHA.

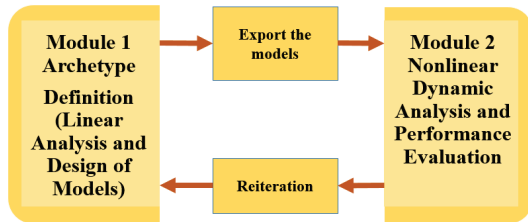


Figure 1: Modules 1 and 2 of the developed software to evaluate seismic force modification factors for BTFs

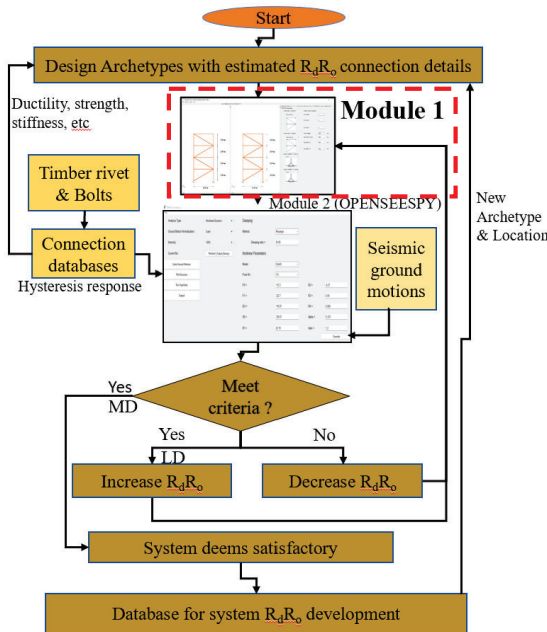


Figure 2: Process to evaluate seismic force modification factors for BTF (LD: Limited ductility; MD: Moderately ductile frames)

3 FRAME ANALYSIS SOFTWARE

Module 1 was developed using Python [6] to calculate loading, analysis and design BTFs. The development of module 2 is in progress to perform NLTHA with the OpenSeesPy library using the exported file from module 1. Module 1 software interface includes a set of general and specialized tabs menus that enables users to create an archetype and, subsequently, analyze and design it in a

step-by-step procedure. The steps followed are based on principles of the capacity-based design approach, as explained and demonstrated below in sections 3.1 to 3.9

3.1 PROJECT INFORMATION

In this section, the user is asked to input the model's name, description, revision number, the engineer's name, and the checker's name, as shown in Figure 3. The software automatically assigns the name to the file based on the input provided. It is noted that properly labelling the created archetypes is essential to help manage the large number of archetypes.

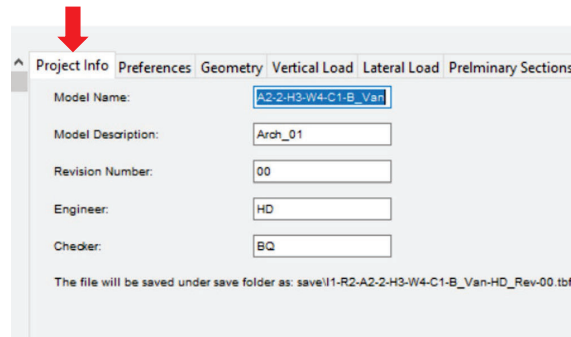


Figure 3: Software interface: project information

3.2 PREFERENCES

In this section, the user selects the unit system (metric or imperial), design code (currently just CSA O86-19 [2]), the loading code (NBCC 2015 [7] or NBCC 2020 [1]), and the location of archetypes. The software currently incorporates four Canadian cities, as shown in Figure 4. Their associated design load values, such as 1-in-50-year ground snow loads, 1-in-50-year associated rain load, 1-in-10-year and 1-in-50-year wind reference velocity pressures, as well as 5% damped spectral response acceleration (S_a), are embedded and taken from NBCC 2015 [7] and NBCC 2020 [1]. More cities will be added later as the use of the module expands.

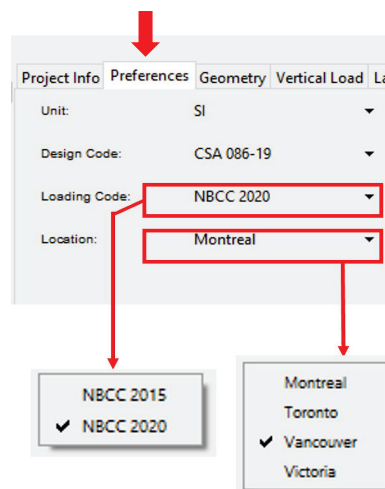


Figure 4: Software interface: preferences

3.3 GEOMETRY AND BOUNDARY DEFINITIONS

This menu possesses two tabs. In the first one, the user inputs the required values to define the geometry of the archetype building, such as the number of storeys, the number of bays, their width in x- and y- directions, and the height of the first and subsequent stories, as shown in Figure 5. The user is also asked to input the type of braced frame in each direction (single diagonal versus cross bracing) and the kind of support condition at the bottom, either pinned or fixed (the pinned support is recommended for BTF). In the second tab, the user can select the locations of the braced bays within the interactive plan view (see Figure 6). The graphic interface will show a view of brace frames in each direction, as shown in Figure 7. By the end of this step, the archetype model's geometry is developed.

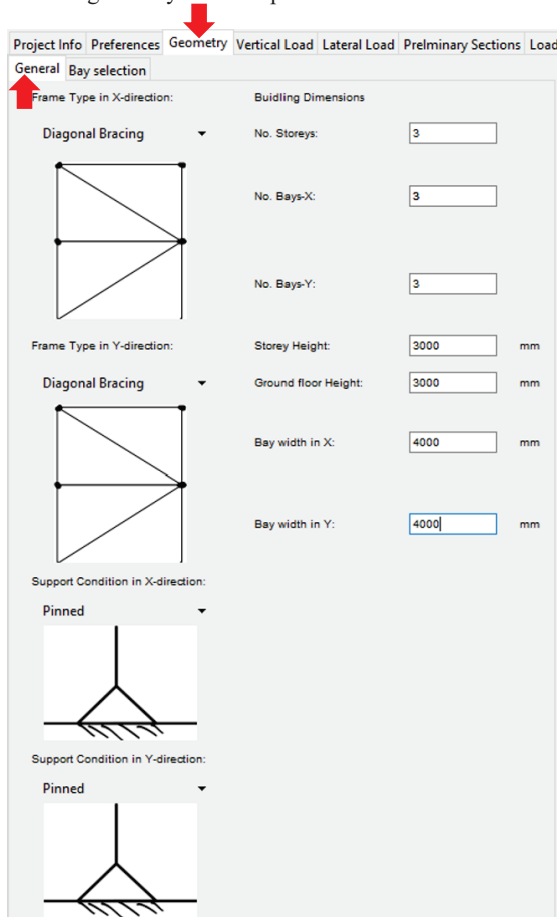


Figure 5: Software interface: geometry definition - braced frame specifications

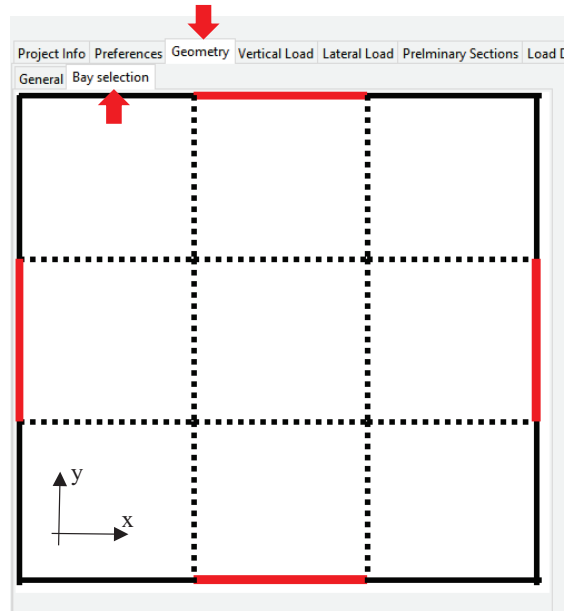


Figure 6: Software interface: geometry definition - braced frame locations

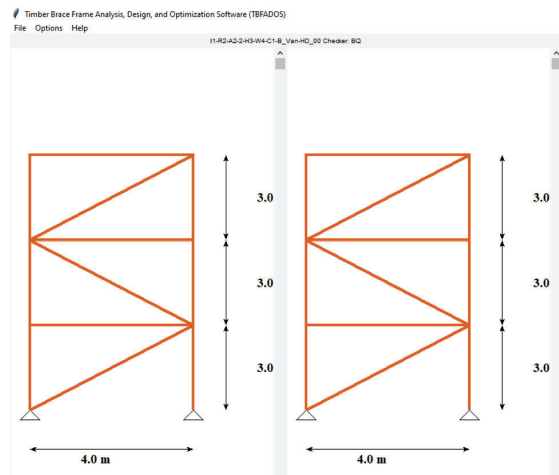


Figure 7: Software interface: geometry creation

3.4 VERTICAL LOAD DEFINITION

In this section, the user inputs the distributed dead and live load with associated factors for calculating the snow load, i.e., wind exposure factor (C_b), slope factor (C_s), and accumulation factor (C_a), as shown in Figure 8. The software will calculate the share of each frame from the vertical loads considering the tributary area of each frame. The seismic weight of the archetype building is calculated based on the input provided in the section, according to the selected loading code. It is noted that the BTFs, as a part of SFRS, do not support any vertical load. The ability to support the vertical load in addition to the lateral load will be added in future revisions of the module.

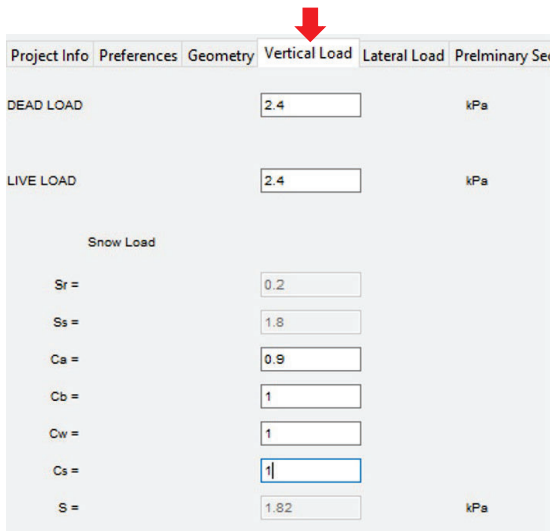


Figure 8: Software interface: vertical load

3.5 LATERAL LOAD DEFINITIONS

This software section contains two tabs: one dedicated to wind load calculation and the other to seismic load, as shown in Figure 9 and Figure 10, respectively. To calculate the wind pressure, the user needs to select the importance category of the building, i.e., low, normal, high, or post-disaster, as well as the option to calculate the wind load; for either the ultimate limit state (ULS) or serviceability limit state (SLS). After that, the software will automatically select the appropriate values for the exposure, topographic, and external and internal pressure factors. The user can choose a factor of 2 or 2.5 for the gust factor. It is noted that the wind load calculation is used solely in period calculations based on the Rayleigh method in module 1 of the developed software.

In the seismic tab (See Figure 10 (a) to (c)), the user is asked to input the necessary values to calculate the induced lateral seismic loads based on the equivalent static load method according to NBCC 2015 or NBCC 2020, e.g., the soil type (Class A to E), importance category, and accidental eccentricities. The spectral acceleration values (S) are automatically calculated based on the archetype location, with reference values anticipated in the preference menu (S_a). One significant difference between NBCC 2015 [7] and NBCC 2020 [1] is the introduction of seismic design categories (SC) in the 2020 version of NBCC [1], which will be determined as shown in Figure 10 (c). Another difference is the substantially higher seismic design load adopted in NBCC 2020 for several major cities in Canada. In addition, the user can select ductility-related force modification, overstrength-related force modification factors, and the R_d and R_o factors, respectively, for each direction. The R_d and R_o factors are also used to calculate the estimated inelastic drifts of each floor. Additionally, the period of the structure is calculated using four different methods shown in Figure 10 (c); or can be overruled by the user. The period calculation method selected by the user will be used for base shear calculation (the default value is the

NBCC's recommended relationship, depending on the height of the archetype solely). Finally, the software will calculate the base shear total force in each direction based on the information provided in this sheet.

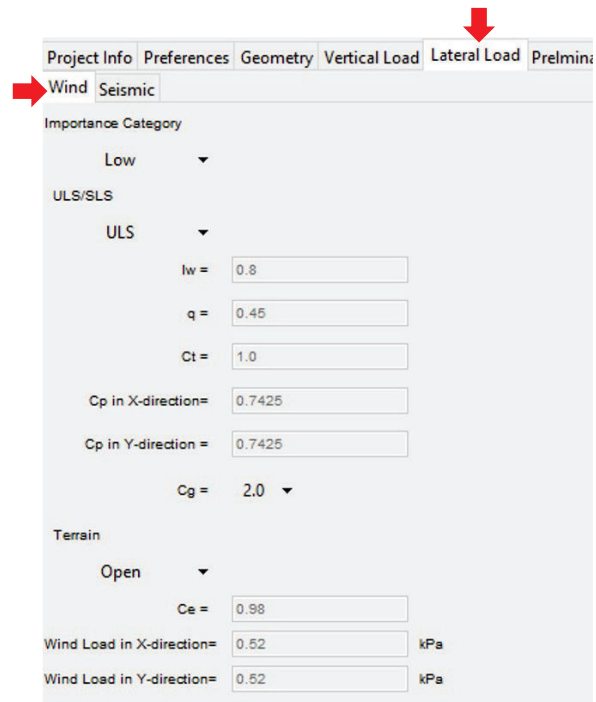
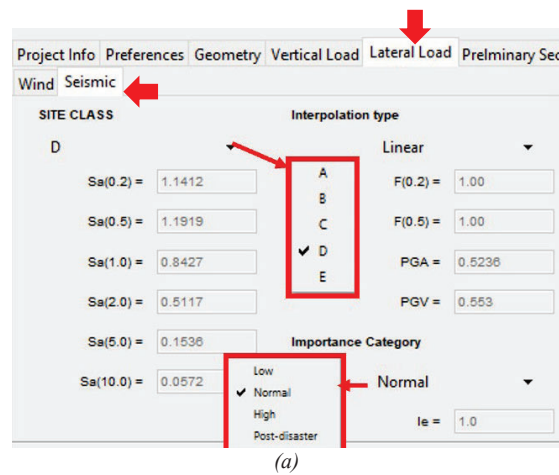
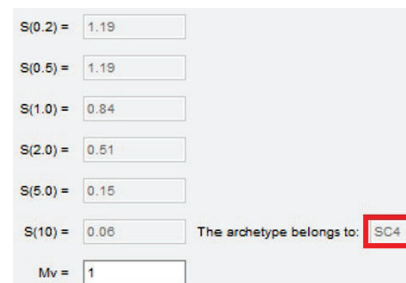


Figure 9: Software interface: lateral load – wind



(a)



(b)

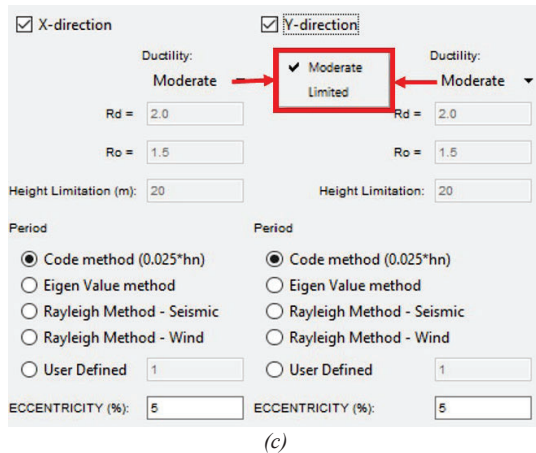


Figure 10: Software interface: lateral load – earthquake

3.6 SECTION DEFINITIONS

In this software interface section (See Figure 11), the preliminary sections and associated dimensions and materials are assigned to the braces, beams, and columns. The available products are sawn lumber and glulam, with different species and grades. In addition, the connection types for the end brace connections (dissipative connections) can be either timber rivet or bolted connection. The need to limit the choices to these two dowel-type connections is because background load-slip data on these connections have been obtained by experiments [8]. Other types of connections or fuses can be incorporated in the future.

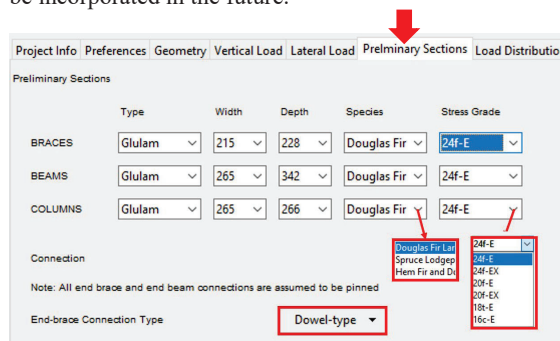


Figure 11: Software interface: preliminary sections

3.7 DIAPHRAGM DEFINITION AND TWO-DIMENSIONAL (2-D) FRAME SELECTION

In this menu, as shown in Figure 12, the diaphragm type (flexible versus rigid) can be selected to distribute the seismic-induced forces among the frame within $-z$ floors. The three-dimensional archetype produced at the beginning is loaded, while the analysis and design will be performed on the chosen 2-D frames, as suggested by CCMC [3] and FEMA P695 [4] guidelines. The BTFs are then analysed and designed based on the selected design loads. The load distribution and results are shown in Figure 12. Figure 13 shows the load distribution at different floor levels of the selected frame in the graphical interface. The period of the structure is calculated and

reported using different methods, as shown in Figure 14. The variability of results for different period calculation methods indicates the need for investigating this issue more profoundly, as the current equation for the braced frames ($0.025h_n$; in which h_n is the building height) [1] is empirically obtained for the steel braced frames.

3.8 ANALYSIS

In this menu, as shown in Figure 15, running the analysis performs the linear static analysis with the option to include p -delta effects. The axial force for the braces is displayed in the graphical interface, along with the absolute elastic displacement. The elastic and plastic drift can be calculated (See Table 1) and compared with allowable values based on the importance category of the building specified in section 3.5. The analysis engine is created based on the matrix structural analysis method (displacement method), fully verified against third-party commercial software, SAP2000 [9].

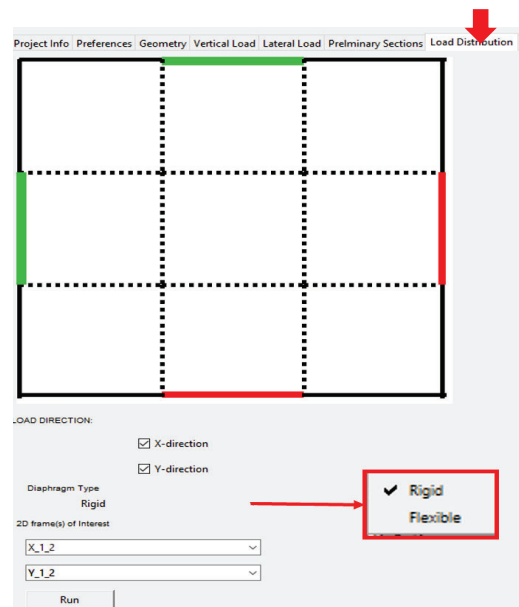
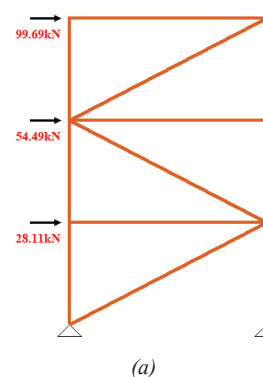


Figure 12: Software interface: load distribution among the frames



(a)

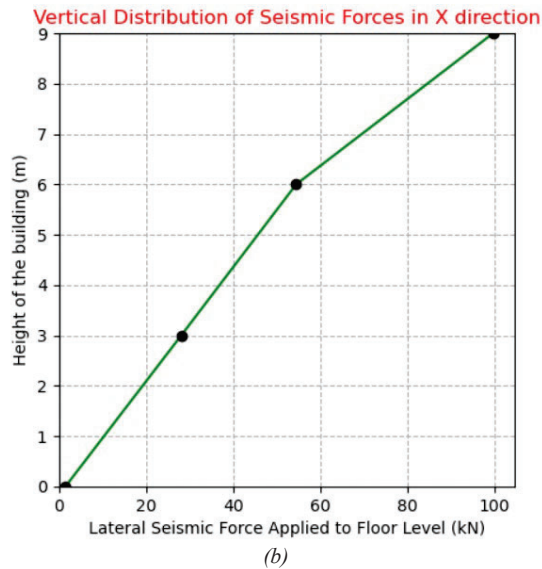


Figure 13: Software interface: sample results for load distribution among the frames

X-direction Periods	
Code Method	2.25E-01
Eigen Value Method	6.00E-02
Rayleigh Method (Seismic)	3.29E-02
Rayleigh Method (Wind)	3.61E-03

Figure 14: Software interface: period calculation

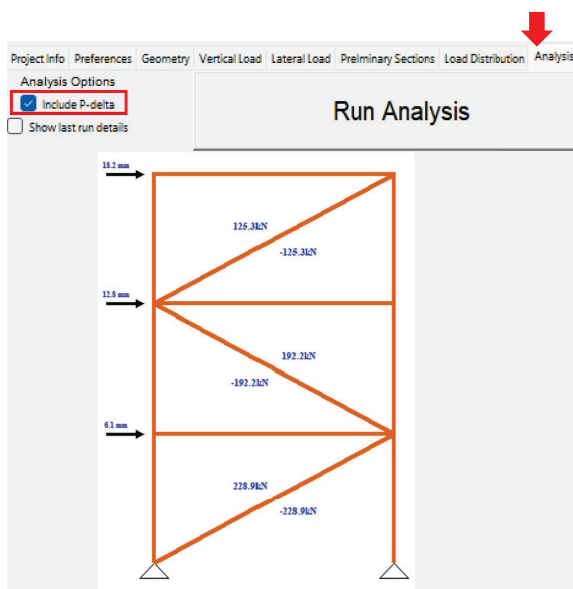


Figure 15: Software interface: analysis results – brace force and displacements

Table 1: Software interface: analysis results – drift calculations for three floors in X-direction

No. Floor	Absolute Displacement (mm)	Elastic Drift	Allowable Drift	Plastic Drift	Status
1	6.106	0.0020	0.025	0.0061	OK
2	12.733	0.0023	0.025	0.0066	OK
3	18.238	0.0018	0.025	0.0055	OK

3.9 DESIGN

This module segment has two tabs: one dedicated to designing dowel-type end brace connections; and the other for the design of members. The latter consists of three subsequent tabs devoted to braces, beams, and columns. Only the brace design interface is discussed in this paper.

3.9.1 End brace connections

For the end brace connection design, two types of fasteners are considered: bolts and timber rivets, due to the availability of the test results for these specific applications [8]. To keep the scope of the designed connection configurations manageable, four patterns for the bolted connections (C1-B, C1-B-R, C2-B, and C2-B-R) and two patterns for the riveted connections (G5-40-12 and G5-65-10) are selected as standard connection types, as shown in Figure 16 (a). The connection patterns for the C1-B and C2-B connection types are shown in Figure 17. C1-B-R and C2-B-R possess the same pattern as C1-B and C2-B, respectively, but were reinforced with self-tapping screws. G5-40-12 and G5-65-10 consist of twenty 5x40 and 5x65 timber rivets, respectively, with 25 mm spacing in both directions. The user can either revise the default design parameters for each type of standard connection, such as modification factors (Figure 16 Figure 16 (b)), fastener specifications (Figure 16(c)), main and side member properties (Figure (d) and (e), respectively), or assign a scale factor (Figure (a)) to satisfy the strength requirement for the end brace connections, i.e., the strength of the end brace connection exceeds the force calculated in Section 3.8 (Figure 16 (f)).

An additional feature within this section is intended to perform a parametrization task in which the hysteresis loops of the connections are quantified by selecting a model. While this step is not vital for the archetype analysis and design within module 1, it is necessary to produce the required input to perform nonlinear dynamic analysis in module 2. The SAWS model, illustrated in Figure 18 Figure 18 (a), available in OpenSeesPy [5], was selected to model both bolted and timber rivet connections, and is appropriate for modelling timber dowel-type connections in general. While this part of the module has been fully developed, it has not yet been discussed herein, as a thorough discussion of the subject is deemed outside the scope of this paper. However, the results of the parametrization exercise for the six types of standard connections mentioned above are summarized in Table 2. The test results compared to the SAWS model

with the obtained parameters are shown in Figure 18 (b) and Figure 18 (c) as examples for C1-B and C2-B.

Figure 16(a) shows the software interface for selecting a connection type. The 'Dowel Connection' section is active. Under 'Design for Frame in X-direction', the 'Fuse to design' is set to 2, with a design force (Pf) of 226.87. Under 'Design for Frame in Y-direction', the design force (Tf) is also 226.87. The 'Predefined Connection type' is set to C1-B, with a scale factor of 4. A dropdown menu is open, showing options: C1-B (checked), C1-B-R, C2-B, C2-B-R, C3-B, G5-40-12, and G5-65-10.

(a)

Figure 16(b) shows the 'Design Factors' section. The factors are: $\Phi_w = 0.7$, $\Phi_s = 0.8$, and $\Phi = 0.9$. The 'Service condition factor' is 'Seasoned dry' with $K_{sf} = 1$. The 'Treatment factor' is 'Untreated' with $K_t = 1$. The 'Load duration factor' is 'Short' with $K_d = 1.15$. The 'Service condition factor' is 'Dry' with $K_{sv} = 1$. The 'System Factor' is 'Case 1' with $K_H = 1.1$.

(b)

Figure 16(c) shows the 'Fastener Information' section. The 'Fastener Type' is 'Bolts'. The parameters are: d_f (mm) = 9.5, f_y (MPa) = 250, l_f (mm) = 155.4, Number of shear planes, $n_s = 2$, Number of rows, $n_r = 3$, Number of fastener in row J, $n_c = 3$, and $n_f = 8$.

(c)

Figure 16(d) shows the 'Main Member' section. The properties are: Type: Glulam, Species: D.fir, Angle of load to grain: Parallel, Size: 130x155, $G_2 = 0.49$, thickness (mm) = 152, t_2 (mm) = 130.0, and No. of Shear Planes = 2.

(d)

Figure 16(e) shows the 'Side Plate' section. The properties are: Material Type: CSA 300W steel, Angle of load to grain: Parallel, t_1 (mm) = 12.7, and f_u (MPa) = 450.

(e)

Figure 16(f) shows the 'Results' section. The values are: Connection resistance (brittle) (kN) = 130.85, Connection Strength (kN) = 69.72, Connection resistance (Ductile) (kN) = 69.72, Scaled Connection Strength (kN) = 278.88. A summary box shows: $\geq \max(P_f, T_f) = 226.87, OK$.

(f)

Figure 16: Software interface: design – end brace connections (a) design force, standard connection type and scale factor (b) design factors (c) fastener information (d) main member (e) side member (f) results satisfying strength requirement

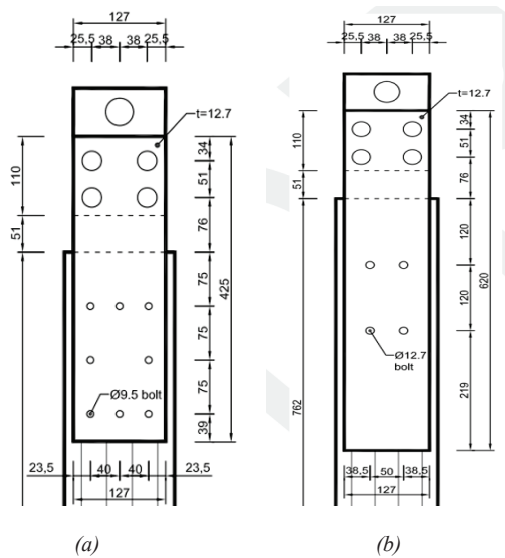
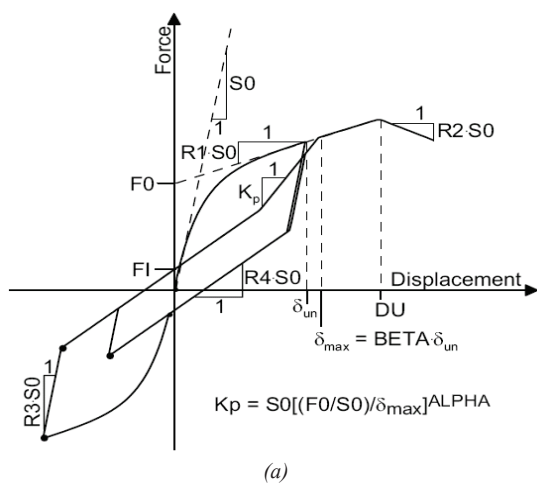
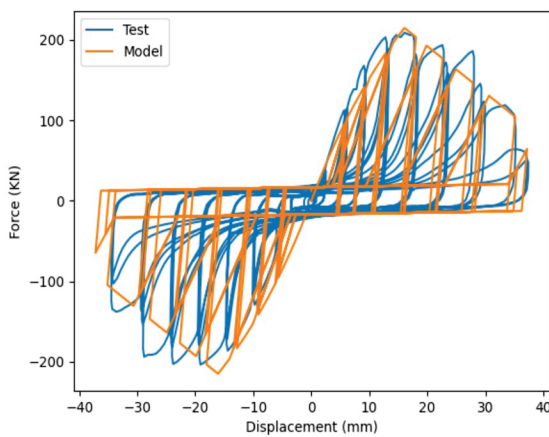


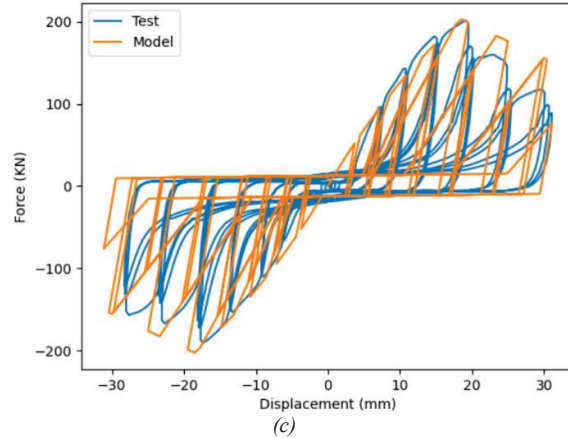
Figure 17: Sample standard end brace connections (a) C1-B (b) C2-B



(a)



(b)



(c)

Figure 18: (a) SAWS model [5] (b) C1-B: test versus SAWS model (c) C2-B: test versus SAWS model

Table 2: SAWS model parameters for standard connection types

Specimen Label	C1-B	C1-B-R	C2-B	C2-B-R	G5-40-12	G5-65-10
F0	245.7	242.7	290.6	218.33	109.4	137.1
FI	16.87	15.31	12.56	15.96	7.51	5.13
DU	16.07	27.38	18.49	38.04	7.51	6.4
S0	19.35	26.61	15.07	17.34	69.20	86.36
R1	0.17	0.035	0.14	0.03	0.002	0.004
R2	-0.29	-0.07	-0.27	-0.12	-0.08	-0.04
R3	4.29	4.2	3.33	4.55	0.82	1.16
R4	0.006	0.01	0.007	0.0092	0.001	0.001
Alpha	0.33	0.32	0.68	0.03	0.03	0.78
Beta	1.1	1.1	1.2	1.08	1.05	1.1

3.9.2 Members

After designing the end brace connections, where energy can be dissipated through yielding, it is necessary to design other components, namely braces, beams, and columns. The members are intended to remain elastic and undamaged, based on the capacity-based design principle. Figures (a) to (c) illustrate the details of designing a brace as an axial member for tension and compression, following CSA O86-19 [2]. Capacity protection is ensured by applying an over-strength factor, Figure 19 (b) and (c), for compression and tension, respectively. Although a factor of 1.1 is used in Figure 19 for demonstration purposes, this value could be increased based on the available test results and the design engineer's judgement. Work is currently underway to develop appropriate values for this factor based on a review of the typical coefficient of variation of connection test data that would meet the philosophy in CSA O86-19 [2] of designing capacity-protected elements based on the 95th percentile of ultimate strength of the energy dissipative connection.

Brace to design: 10

Pf (kN): 124.52

Tr (kN): 124.52

Type: Glulam

Width (mm): 175

Depth (mm): 152

Species: Douglas Fir Larch

Grade: 24f-E

L (mm): 5000.00

Effective-X: 1

Effective-Y: 1

Ld (mm): 5000.00 Area (mm²): 20800.00

Lb (mm): 5000.00

fc (Mpa): 30.2

E (Mpa): 12800

E05 (Mpa): 11136.00

(a)

Compression Tension

Overstrength factor: 1.1

Kz0g: 0.88

Z (m³): 0.13

KeX: 1

KeY: 1

Kc: 0.25

CoX: 32.89

CoY: 28.57

Cc: 32.89

Load duration factor: Short

Case: 1

Service Type: Dry

Product: Untreated Lumber

Fc (MPa): 38.20

Stress Ratio: 0.76589 <= 1, OK

Pr (kN): 178.84 >= 136.97, OK!

(b)

Compression Tension

Overstrength factor: 1.1

Load duration factor:

Connection Type: Bolted

Case:

No. rows: 1

Service Type:

Bolt Diameter (mm): 9.5

Product:

Φ: 0.9

ftN (MPa): 20.40

Short

K_d = 1.15

1

K_H = 1.1

Dry

K_{St} = 1

Untreated Lumber

K_T = 1

K_{SE} = 1

FtN (MPa): 25.81

FtG (MPa): 19.35

TrN (kN): 579.27 >= 137.61, OK!

TrG (kN): 463.24 >= 137.61, OK!

Tr (kN): 463.24

Stress Ratio: 0.29706 <= 1, OK

(c)

Figure 19: Software interface: design – braces (a) selected brace force and section and general design parameters (b) design parameters for compression (c) design parameters for tension

4 RESULTS

After the results of the load distribution calculation, analysis, and design of connections and members are obtained; the last two tabs of the module should be accessed. They include the summary of the results and the export process of the model details and results to use in module 2 for performing NLTHA.

4.1 RESULTS

Figure 20 demonstrates a sample result summary of this module of the software. The geometry of the model includes the node coordinates (Figure 20 (a)), member types with their associated material types, section size, species, and grade, which the user can verify (Figure 20 (b)). The maximum governing stress ratio and status are also presented (Figure 20 (b)). Finally, the user can verify the number and type of end-brace connections with the scale factor used for design and the associated SAWS model parameters (Figure 20 (c)).

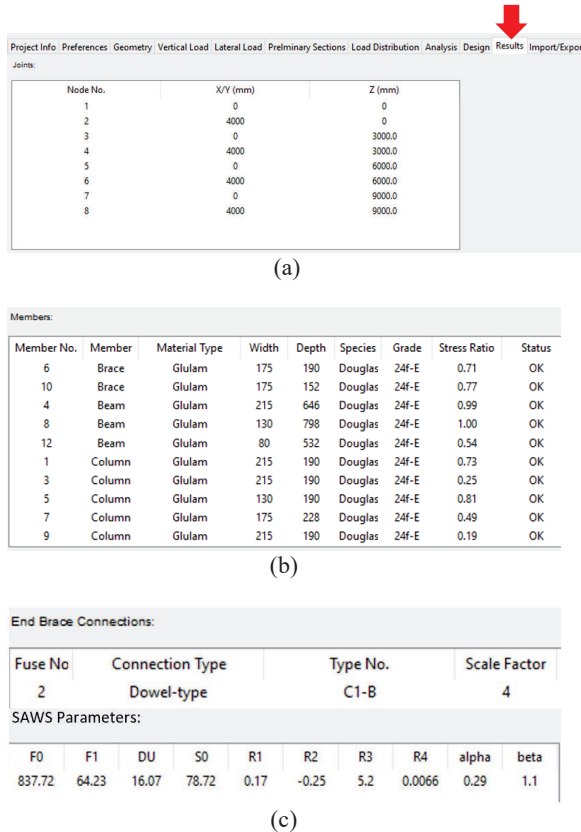


Figure 20: Software interface: results (a) node coordinates (b) members and their associated types, material, sections, stress ratios (c) end brace connection types and associated SAWS model parameters

4.2 EXPORT TO MODULE 2

In the last section of the first module of the software, the results are exported as a file with the .py extension, which can be imported to module 2 to perform nonlinear dynamic analysis using the OpenSeesPy analysis engine [5].

5 SUMMARY AND CONCLUSIONS

This research project aims to contribute to developing design provisions on BTFs that could be implemented in the next edition of CSA O86-19 [2]. As the initial part of the research, a software module responsible for analysing statically (with the option to include p-delta) and

designing a variety of archetype braced timber frames based on the principle of capacity-based design. The methodology established in the developed module provides specific connection details and system specifications permitted to use with the stated ductility-related seismic force modification factors specified in NBCC [1 & 7], namely limited and moderate ductility.

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