Advanced Topics in Seismic Analysis and Design of Mid-rise Wood-Frame Structures

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INTRODUCTION

- The 2015 National Building Code of Canada raised the limit of wood-frame construction from 4- to 6-storeys (mid-rise)
- A Mid-rise Wood-Frame Construction Handbook was developed by FPInnovations to provide guidelines for design and construction of mid-rise wood-frame buildings according to 2015 NBCC
- This paper provides information on some of the topics covered in the Handbook related to the seismic analysis and design of mid-rise wood-frame buildings:
  - Determination of building period
  - Linear dynamic analysis of wood-frame structures
  - Diaphragm classification
  - Capacity-based design for wood-frame structures
  - Design of wood-frame buildings on concrete podiums

Building Period

- Significant role in calculation of the design base shear
- Preliminary design to be done using the NBCC formula

$$T_a = 0.05$$

- Once shearwall detailing is completed (preliminary design), the period can be recalculated using methods of mechanics such as Rayleigh's method

$$T = 2\pi\sqrt{\frac{\sum_{i=1}^{n}}{g\sum_{i=}}}$$

- Make sure period is not exceeding the upper limit of $2T_a$

Gypsum Wallboard and Stucco

- Significant influence on the building period
- Although gypsum wallboard shall not be taken in calculating the resistance, its stiffness and that of the stucco shall be included when determining the building period
- The initial stiffness can be calculated using the slope between the points of 0% and 40% of the capacity (ASTM E2126)
- Gypsum wallboard and stucco shall not be accounted for in lateral drift calculations (as not part of SFRS per NBCC)

Linear Dynamic Analysis (LDA)

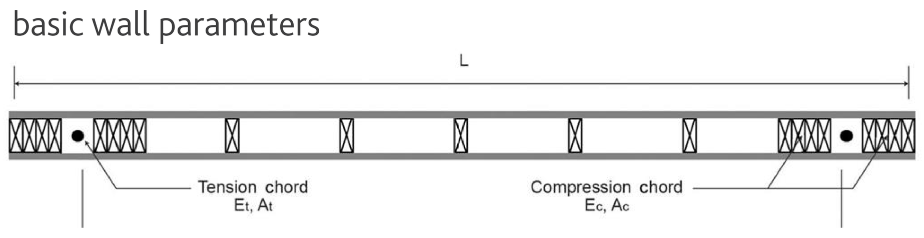
- Use of LDA should be encouraged in analysis and design
- Benefits of LDA include:
  - Considers the effect of higher mode participation
  - Better determines building deflections and storey drifts
  - Allows for three-dimensional modelling
  - Reduces the minimum torsional effect required under the ESFP
  - Better considers the effect of vertical changes in RdRo (podiums)
- Challenge: the stiffness properties and other input parameters are not easily determined

Proposed Steps for LDA

- Step one (preliminary analysis): Perform an initial analysis and design to determine the properties of each wall of the LLRS
- Allows designers to get the information required to determine stiffness and deflection characteristics of the shearwalls
- Step two: Use the preliminary analysis info to generate input data for LDA for a multi-level structure
  - The design base shear must be the larger of:
  - The dynamic design force Vd
  - 100% of static design force V

Properties of Shear Walls for LDA

- Shear walls can be modeled as beam elements in commercial software
- Calculations for equivalent beam element properties (flexural and shear stiffness) are given based on the basic wall parameters



$$b = L \qquad E = E_{c,eq} \qquad t_{eq} = \frac{12 I_{tr}}{L^3}$$

$$G = \frac{1.2}{\left(\frac{t_p}{B_v} + 0.0025\frac{e_n s t_p}{v_n}\right)}\frac{t_p}{t_{eq}} = \frac{1.2}{t_{eq}\left(\frac{1}{B_v} + 0.0025\frac{e_n s}{v_n}\right)}$$

Deflections of Shear Walls

$$\Delta_i = \Delta_{b,i} + \Delta_{s,i} + \Delta_{n,i} + \Delta_{a,i} + \Delta_{r,i}$$

Where: $\Delta_{b,i}$ is deflection of i-th storey due to bending

$\Delta_{s,i}$ is deflection of i-th storey due to panel shear

$\Delta_{n,i}$ is the deflection of i-th storey due to nail slip

$\Delta_{a,i}$ is the deflection of i-th storey due to wood plate bearing and anchorage slip

$\Delta_{r,i}$ is the deflection of i-th storey due to rotation at the bottom of the shear wall

Deflection Components

$$\Delta_{b,i} = \frac{V_i H_i^3}{3(EI)_i} + \frac{M_i H_i^2}{2(EI)_i} \qquad \Delta_{s,i} = \frac{V_i H_i}{L_i B_{v,i}} \qquad \Delta_{a,i} = \frac{H_i}{L_i} d_{a,i}$$

$$\Delta_{n,i} = 0.0025 H_i e_{n,i}$$

where:

Mi = overturning moment at level i

Hi = the height of shear wall at i-th storey

$(EI)_i$ = effective bending stiffness of shear wall at i-th storey

L_i = length of shear wall at i-th storey

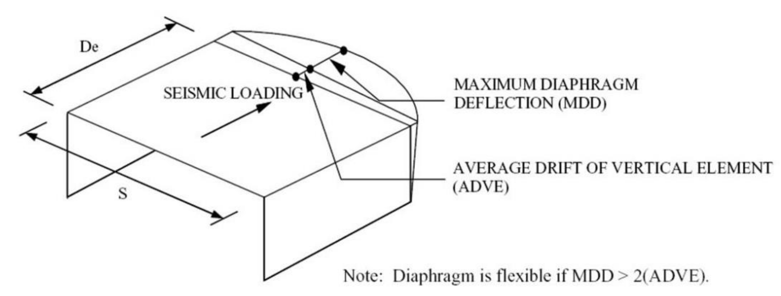
$B_{v,i}$ = shear-through-thickness rigidity of wall panels

$e_{n,i}$ = nail deformation for shear wall at i-th storey

$da_{,i}$ = sum of vertical deformation at i-th storey due to wood plate bearing and anchorage slip

In-Plane Diaphragm Flexibility

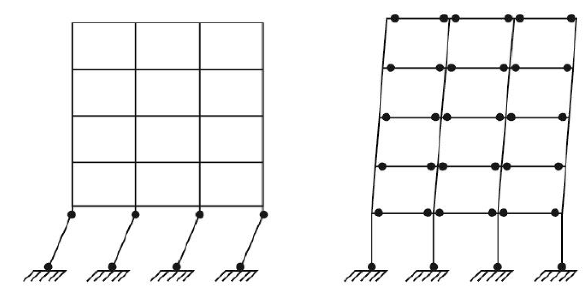
- In-plane diaphragm stiffness affects the overall response of the building subjected to lateral forces
- Whether a diaphragm is treated as flexible, rigid, or semi-rigid, depends on the in-plane stiffness of the diaphragm relative to the stiffness of the vertical LLRS underneath
- Suggested to use ASCE 41-13 (flexible if: MDD > 2 ADVE)



Note: Diaphragm is flexible if MDD > 2(ADVE).

Capacity Based Design

- Widely used for seismic design of concrete and steel structures, but only recently made inroads into wood design standards
- By choosing desirable deformation modes of the SFRS, certain parts of it are designed for yielding and energy dissipation("plastic hinges" or "dissipative zones")
- All other structural elements are designed not to yield(capacity protected and designed based on over-strength)



CSAO86 Provisions on Capacity Design

- Increased design loads on critical system components and force transfer elements
- Anchor bolts, inter-storey connections, and hold-downs to be designed for seismic loads that are at least 20% greater than the force that is being transferred
- Intent: To ensure that the desired ductile nail yielding is achieved throughout the structure without any failure in the hold-downs and shear transfer connections
- To avoid a soft-storey mechanism at the bottom two storeys, check for over-capacity ratio of the vertical SFRS (C_2/C_1), where:

$$C_i = \frac{V_{ri}}{V_{fi}}$$

V_{ri} = Factored resistance of SW at storey "i"

V_{fi} = Factored seismic shear at storey "i"

- It is recommended that the C_2/C_1, C_3/C_2, C_4/C_3 and C_5/C_4 ratios be checked for 5-and 6-storey buildings
- Diaphragm coefficients C_{Di} are also introduced, being the lesser of C_i or 1.2
- Handbook contains main steps of the design process for shearwalls and diaphragms

Podium Buildings

- Several storeys of wood-frame construction built over one or more storeys of elevated concrete podium
- Especially prevalent in the Western North America during the last two decades

Current Code Status and Approaches for Podium Buildings

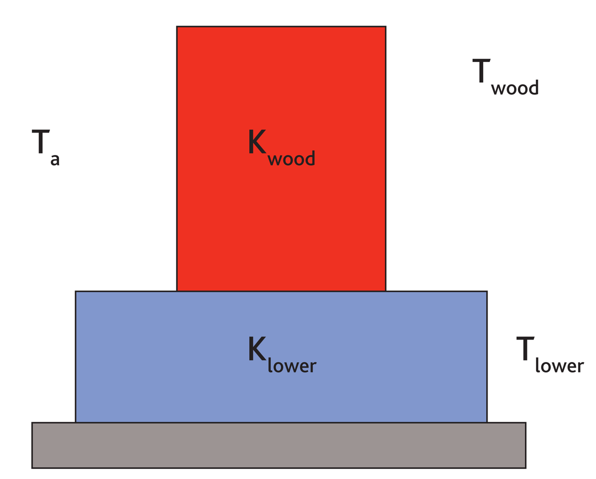
- Not explicitly included in 2015 NBCC or 2014 CSA O86
- Designers can choose between two methods that implicitly cover podium buildings in NBCC
- **First:** Linear Dynamic Analysis (LDA) as default NBCC approach
  - Analytical model should include both concrete and wood portions with their own strength and stiffness properties
  - Distribution of linear shear forces along the height is obtained
  - Corresponding R_dR_o factors for each storey are used to determine the design shear forces

NBCC Equivalent Static Procedure

- Seismic interaction of concrete and wood-frame portion is ignored
- Wood portion is treated as a separate building supported on the ground designed with its own Rd Ro
- Shear forces and overturning moments from the wood portion are applied to the concrete slab below
- Concrete podium designed as separate building with its own Rd and Ro factors
- No criteria in main body of NBCC when to use this approach
- Commentary J note 151 states that such procedure can be used when the stiffness $K_{podium} > 3\ K_{wood}$

ASCE-7 Two-stage Analysis Procedure

- Two-stage procedure can be used if the structure complies with both requirements:
  - Stiffness of the podium Klower ≥ 10 times that of the wood K_{wood}
  - Period of the entire structure Ta ≤ 1.1 T_{wood} (as a separate structure)



CONCLUSIONS

- The Mid-rise Woof-Frame Construction Handbook provides guidelines for early adopters and mainstream practitioners to design and construct mid-rise wood frame construction in compliance with the 2015 NBCC, Provincial Codes, and 2014 CSA O86
- A total of 42 industry, research and design experts have been involved in the development of the Handbook
- The information in the Handbook shall be used in addition to the info already available in CWC's Wood Design Manual (2010), the APEGBC Bulletin for design and construction of 5-and 6-storey wood-frame construction, and the 2013 Quebec guidelines from Régie du bâtiment du Québec