prEN 1998-3:2022 Assessment and retrofit of timber buildings

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THE NEW DRAFT OF EN1998-3

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

prEN 1998-3

CEN/TC 250/SC 8 **N 1236**

Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings and bridges

Eurocode 8 : Calcul des structures pour leur résistance aux séismes - Partie 3 : Évaluation et renforcement des bâtiments et ponts

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben - Teil 3: Beurteilung und Ertüchtigung von Gebäuden und Brücken

CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

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Chapter 10 | Specific rules for timber buildings

Timber Diaphragms

Figure 10.1 — Diaphragm typologies: a) single straight sheathed diaphragm with squared timber joists; b) floor with clay tiles over joists; c)/d) floor built with the so-called "malta-paglia" (mortar-straw) technique, beneath and above views

Timber Frames

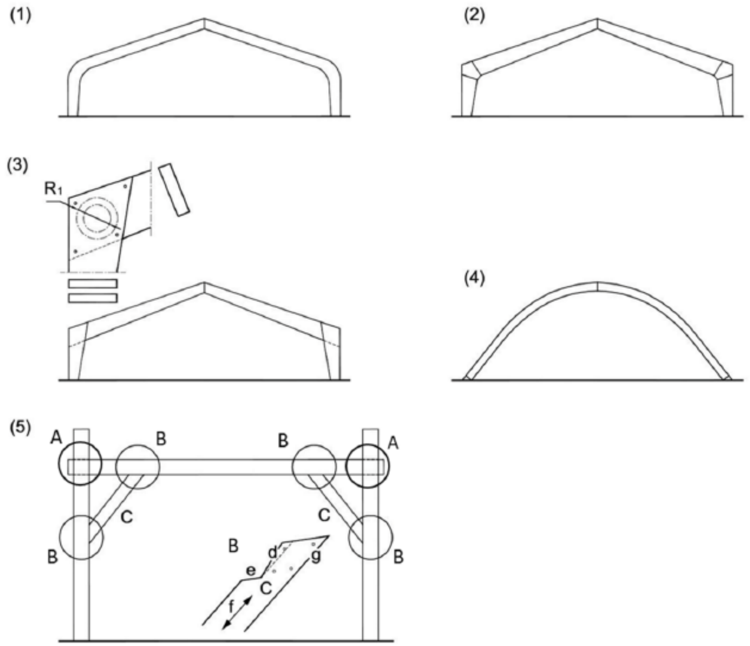


Figure 10.3 — Timber frames addressed: 1) frames with relatively thin lamellas (glued), 2) finger joint (glued) connections, 3) dowelled connections, 4) arches, 5) traditional frames

Carpentry Connections

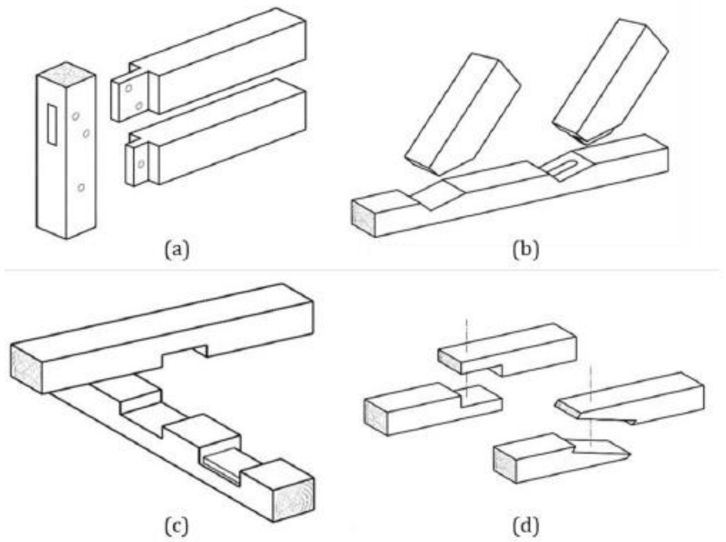
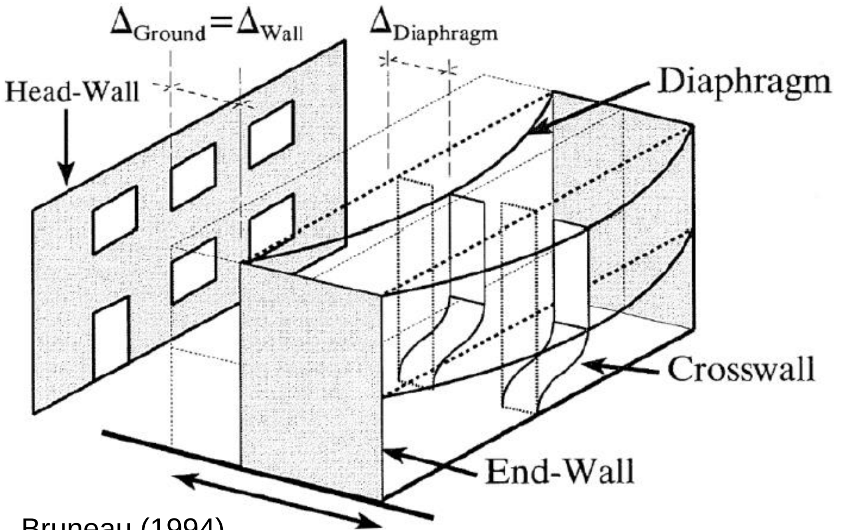


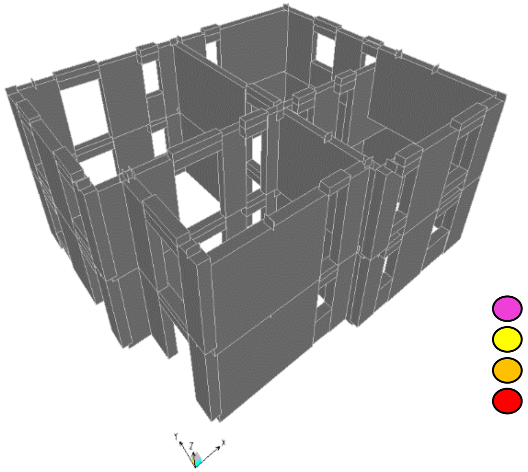
Figure 10.4 — Examples of carpentry connections: (a) Through pinned mortise and tenon (a') Blind pinned mortise and tenon (b) Notched joint between main rafters and tie-beam (b') A skewed tenon may be used to help in keeping all timber pieces co-planar (c) Half-lap joint (c') Cogged half-lap joint (d) Halved scarf-joint (d') Scarf-joint with under-squinted ends

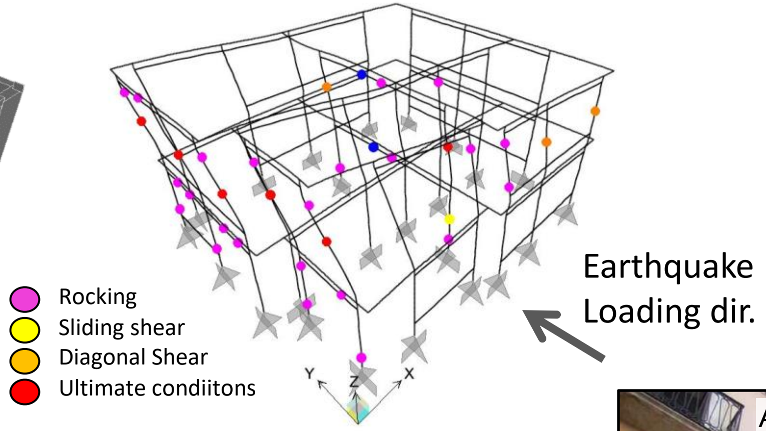
CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS



Bruneau (1994)

Flexible diaphragms






Augenti and Parisi (2015)


Penna et al. (2007)


Penna et al. (2007)


Dizhur et al. (2011)

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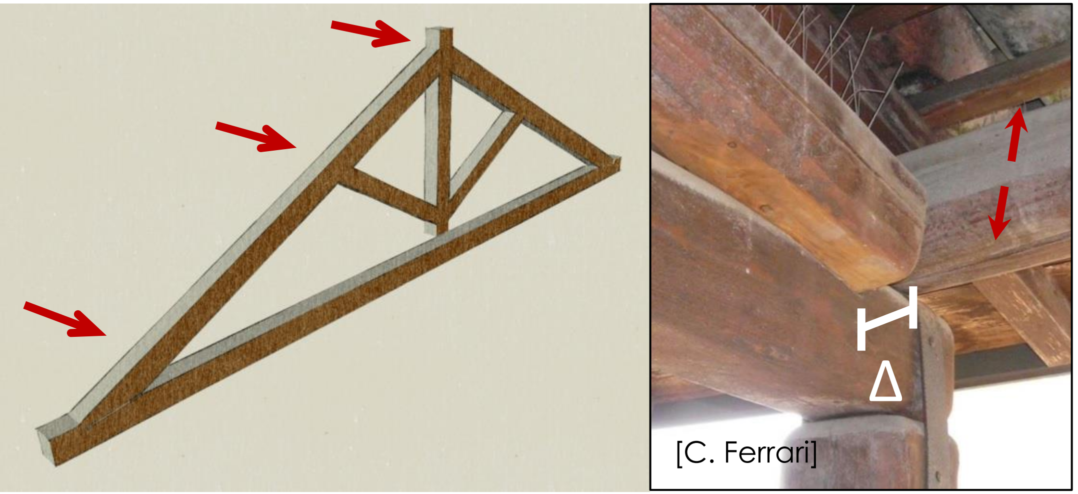
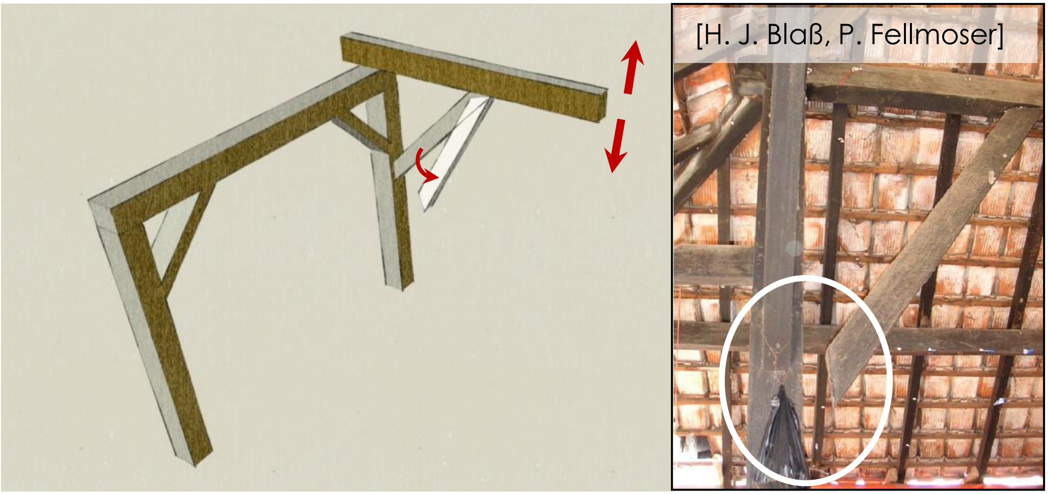
ANNEX C | SUPPLEMENTARY INFORMATION FOR TIMBER STRUCTURES



Dislodging of a single-step joint (2012 Emilia earthquake)



Loss of contact surface in a single-step joint (2006 Yogyakarta earthquake)

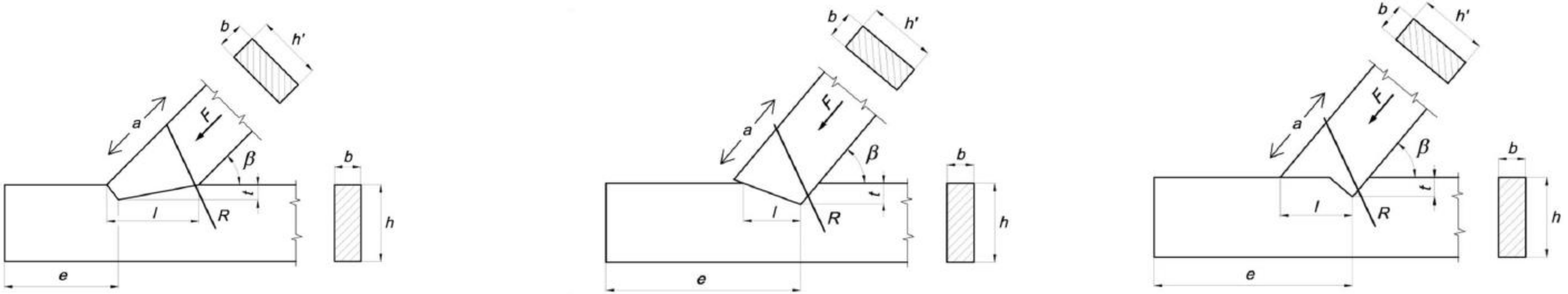


Figure C.1 — Example of reinforcement to be applied to the single-step connection

CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

General rules

$$X_d = \varphi \cdot \frac{X_k \cdot \eta}{\gamma_R}$$

It's a parameter depending on the condition rating and the knowledge level

Knowledge level	Condition assessment factor – φ
KLM1 – Minimum knowledge	Refer to D3 class φ-value
KLM2 – Average knowledge	Refer to the φ-value corresponding to the degradation class immediately worse than the one obtained on the basis of the inspections
KLM3 - High knowledge	Refer to the φ-value corresponding to the degradation class obtained on the basis of the inspections

5.4.4 (1) a) **KLM1 (Minimum knowledge)** is attained when no direct information on the mechanical properties of the construction materials is available, either from original design specifications or from original test reports. Default values should be assumed in accordance with standards at the time of construction, accompanied by limited in-situ testing in the most critical members. In the case of masonry structures, direct testing may be avoided, and reference values of predefined masonry types may be attributed after an extended visual survey of masonry features (according to Table 5.1). In the case of **timber buildings** and **timber members**, direct testing may be avoided provided that an **accurate visual inspection** is performed according to **10.2.4.1**.

5.4.4 (1) b) **KLM2 (Average knowledge)** is attained when information on the mechanical properties of the construction materials is available either (i) from extended in-situ testing; or (ii) from original design specifications complemented by limited in-situ testing. In the case of masonry structures, when original design documents are not available, direct testing may still be avoided, but, in addition to what is required for KLM1, the knowledge should be enhanced by extended non-destructive testing, as specified in Table 5.3 for inspections, which allows a more accurate classification of masonry types in the structure. In the case of pre-1940 timber buildings, when original design documents are not available, direct testing may be avoided, but, in addition to what is required for KLM1, the knowledge should be enhanced by **non-destructive testing**, as specified in Table 10.1.

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KLM1 – Minimum knowledge	Refer to D3 class φ-value
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testing in the most critical members. In the case
avoided, and reference values of predefined
extended visual survey of masonry features (
timber buildings and **timber membe**
provided that an **accurate visual ins**
10.2.4.1.

5.4.4 (1) c) KLM3 (High knowledge) is attained when information on the mechanical properties of the construction materials is available either (i) from comprehensive in-situ testing; or (ii) from original test reports, complemented by limited in-situ testing; or (iii) from original design specifications, complemented by extended in-situ testing. In the case of masonry structures, in addition to what is required for KLM2, direct testing of material properties in the critical areas should be performed, in order to update the reference values of predefined masonry types; material properties should then be defined by using results of tests for updating the reference values for the masonry types. In the case of timber structures, in addition to what is required for **KLM2, (semi) non-destructive testing**, e.g. by resistance drilling, and/or density measurements on small samples in order to define the material properties in the critical zones should be performed (see **Table 10.1**).

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cations complemented by limited in-situ testing.
nal design documents are not available, direct
n to what is required for KLM1, the knowledge
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CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

General rules

Table 10.1 gives an overview of selected methods for assessing the condition of timber structural members through non-destructive testing (NDT) and semi-destructive testing (SDT), based on the two recommendations edited by the **RILEM Technical Committee AST 215** ''In-situ assessment of structural timber''

Table 10.1 — NDT and SDT methods to assess Knowledge Level and Condition assessment of structural timber

Method		Determine species	Measure MC	Locate deterioration	Quantify deterioration	Assess strength	Determine stiffness	Identify hidden details	Knowledge level	Condition assessment
Visual inspection	NDT			Limited					KLM1 - KLM2 - KLM3	✓
Remote visual inspection	NDT			Limited	Limited			Yes	KLM3	✓ (**)
Species identification	NDT	Yes							KLM1 - KLM2 - KLM3	✓
Moisture measurements	NS		Yes						KLM1 - KLM2 - KLM3	✓
Digital radioscopy	NDT			Yes	Limited			Yes	KLM3 (*)	
Ground penetrating radar	NDT		Limited	Limited				Limited	KLM3 (*)	
Infrared thermography	NDT		Limited	Limited				Limited	KLM3 (*)	
Stress waves	NDT			Limited	Limited	Limited	Estimate		KLM2 (*) - KLM3 (*)	✓ (**)
Ultrasound methods	NDT			Limited	Limited	Limited	Estimate	Limited	KLM2 (*) - KLM3 (*)	✓ (**)
Resistance drilling	NDT			Yes	Yes	Limited		Limited	KLM2 (*) - KLM3	✓ (**)
Core drilling	SDT			Yes		Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Tension micro-specimens	SDT					Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Glueline test	SDT		Limited	Limited		Limited			KLM2 (*) - KLM3	✓ (**)
Screw withdrawal	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	
Needle penetration	NDT			Limited		Limited			KLM2 (*) - KLM3 (*)	✓ (**)
Pin pushing	SDT			Yes	Limited	Estimate			KLM2 (*) - KLM3 (*)	✓ (**)
Surface hardness	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	

(*) Not mandatory
(**) If relevant
NDT: Non-Destructive Technique
SDT: Semi-Destructive Technique
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Remote visual inspection	NDT			Li[...]				Yes	KLM3	✓ (**)
Species identification	NDT	Yes							KLM1 - KLM2 - KLM3	✓
Moisture measurements	NS		Yes						KLM1 - KLM2 - KLM3	✓
Digital radioscopy	NDT			Ye[...]				Yes	KLM3 (*)	
Ground penetrating radar	NDT		Limited	Li[...]				Limited	KLM3 (*)	
Infrared thermography	NDT		Limited	Li[...]				Limited	KLM3 (*)	
Stress waves	NDT			Li[...]			[...]e		KLM2 (*) - KLM3 (*)	✓ (**)
Ultrasound methods	NDT			Li[...]			[...]e	Limited	KLM2 (*) - KLM3 (*)	✓ (**)
Resistance drilling	NDT			Ye[...]				Limited	KLM2 (*) - KLM3	✓ (**)
Core drilling	SDT			Ye[...]			[...]e		KLM2 (*) - KLM3 (*)	
Tension micro-specimens	SDT						[...]e		KLM2 (*) - KLM3 (*)	
Glueline test	SDT		Limited	Li[...]					KLM2 (*) - KLM3	✓ (**)
Screw withdrawal	SDT			Li[...]					KLM2 (*) - KLM3 (*)	
Needle penetration	NDT			Limited		Limited			KLM2 (*) - KLM3 (*)	✓ (**)
Pin pushing	SDT			Yes	Limited	Estimate			KLM2 (*) - KLM3 (*)	✓ (**)
Surface hardness	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	

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Table 10.1 — NDT … nt of structural timber

Method									Knowledge level	Condition assessment
Visual inspection	NDT								KLM1 - KLM2 - KLM3	✓
Remote visual inspection	NDT								KLM3	✓ (**)
Species identification	NDT								KLM1 - KLM2 - KLM3	✓
Moisture measurements	NS								KLM1 - KLM2 - KLM3	✓
Digital radioscopy	NDT							Yes	KLM3 (*)	
Ground penetrating radar	NDT							Limited	KLM3 (*)	
Infrared thermography	NDT		Limited	Limited				Limited	KLM3 (*)	
Stress waves	NDT			Limited	Limited	Limited	Estimate		KLM2 (*) - KLM3 (*)	✓ (**)
Ultrasound methods	NDT			Limited	Limited	Limited	Estimate	Limited	KLM2 (*) - KLM3 (*)	✓ (**)
Resistance drilling	NDT			Yes	Yes	Limited		Limited	KLM2 (*) - KLM3	✓ (**)
Core drilling	SDT			Yes		Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Tension micro-specimens	SDT					Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Glueline test	SDT		Limited	Limited		Limited			KLM2 (*) - KLM3	✓ (**)
Screw withdrawal	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	
Needle penetration	NDT			Limited		Limited			KLM2 (*) - KLM3 (*)	✓ (**)
Pin pushing	SDT			Yes	Limited	Estimate			KLM2 (*) - KLM3 (*)	✓ (**)
Surface hardness	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	

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NDT: Non-Destructive Technique
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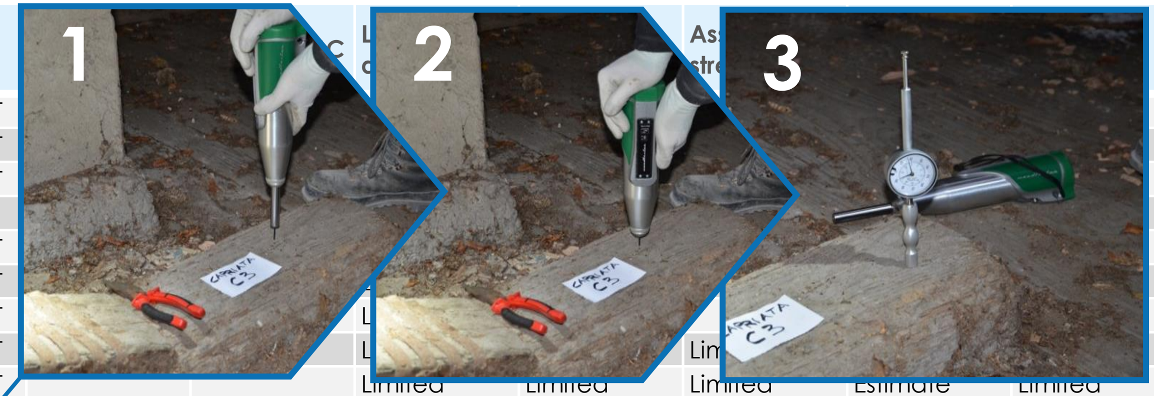

Method			C	L c		As stre			Knowledge level	Condition assessment
Visual inspection	NDT								KLM1 - KLM2 - KLM3	✓
Remote visual inspection	NDT								KLM3	✓ (**)
Species identification	NDT								KLM1 - KLM2 - KLM3	✓
Moisture measurements	NS								KLM1 - KLM2 - KLM3	✓
Digital radioscopy	NDT								KLM3 (*)	
Ground penetrating radar	NDT								KLM3 (*)	
Infrared thermography	NDT			L					KLM3 (*)	
Stress waves	NDT			L		Lim			KLM2 (*) - KLM3 (*)	✓ (**)
Ultrasound methods	NDT			Limited	Limited	Limited	Estimate	Limited	KLM2 (*) - KLM3 (*)	✓ (**)
Resistance drilling	NDT			Yes	Yes	Limited		Limited	KLM2 (*) - KLM3	✓ (**)
Core drilling	SDT			Yes		Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Tension micro-specimens	SDT					Estimate	Estimate		KLM2 (*) - KLM3 (*)	
Glueline test	SDT		Limited	Limited		Limited			KLM2 (*) - KLM3	✓ (**)
Screw withdrawal	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	
Needle penetration	NDT			Limited		Limited			KLM2 (*) - KLM3 (*)	✓ (**)
Pin pushing	SDT			Yes	Limited	Estimate			KLM2 (*) - KLM3 (*)	✓ (**)
Surface hardness	SDT			Limited		Limited			KLM2 (*) - KLM3 (*)	

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NDT: Non-Destructive Technique
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CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

General rules

$$X_d = \varphi \cdot \frac{X_k \cdot \eta}{\gamma_R}$$

Table 5.3 — Values of k_{mod}

Material		Service class	Load-duration of action: Permanent	Long-term	Medium-term	Short-term	Instantaneous
Structural timber (ST), Finger jointed timber (FST), Glued solid timber (GST), Glued-laminated timber (GL), Block glued glulam (BGL), Cross laminated timber (CLT), Solid wood panels (SWP-P, SWP-C), Laminated veneer lumber (LVL), Glued laminated veneer lumber (GLVL), Plywood (PW)[a], Densified laminated wood (DLW)		1 and 2	0,60	0,70	[illegible]	0,90	1,10
Structural Timber (ST), Glued-laminated timber (GL), Laminated veneer lumber (LVL), Ply[illegible] (PW)[a]		3	0,55	0,60	0,70	0,80	1,00
Structural timber (ST)		4	0,50	0,55	0,65	0,70	0,90
Oriented strand board (OSB)	OSB/2	1	0,30	0,45	0,65	0,85	1,10
	OSB/3, OSB/4	1	0,40	0,50	0,70	0,90	1,10
		2	0,30	0,40	0,55	0,70	0,90

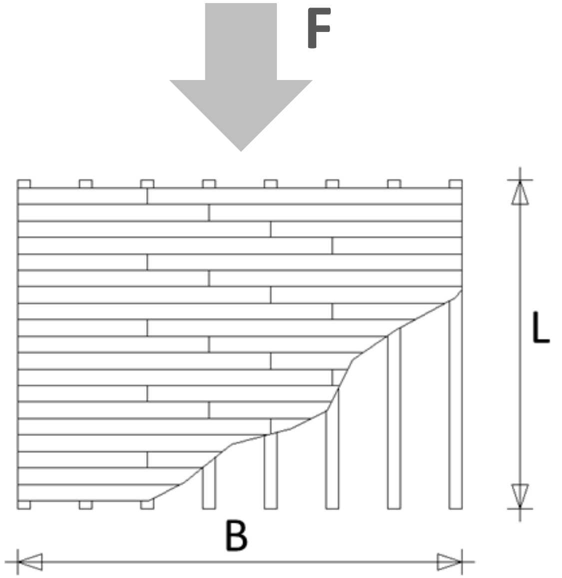
Knowledge level	Condition assessment fa[illegible]
KLM1 – Minimum knowledge	Refer to D3 class φ-value
KLM2 – Average knowledge	Refer to the φ-value [illegible] degradation class immediately worse than the one obtained on the basis of the inspections
KLM3 - High knowledge	Refer to the φ-value corresponding to the degradation class obtained on the basis of the inspections

Condition assessment factors (φ) for timber diaphragms

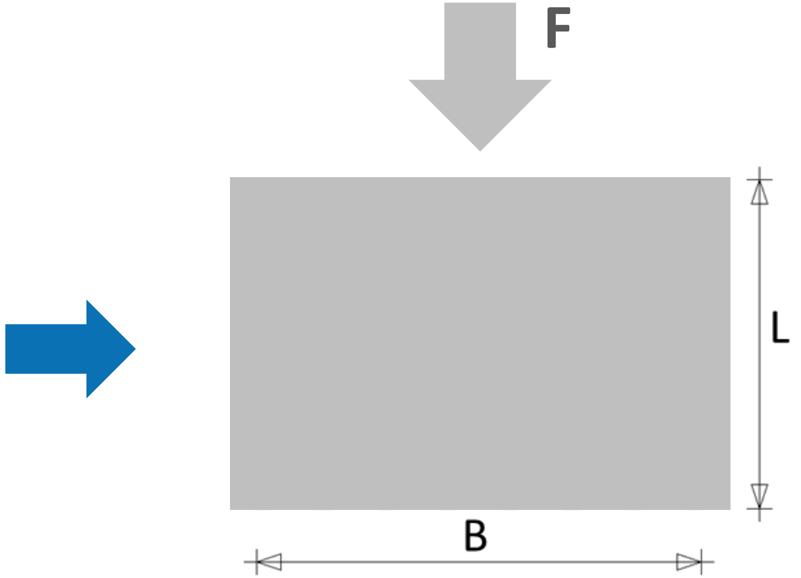
Condition rating	Condition description	As-built	(*) Retrofitted
D1 - Good	Timber free of borer; no signs of past water damage*; little or no nail rust; floorboard-to-joist connection tight, coherent and unable to wobble	1.00	1.00
D2 - Fair	Little or no borer; little or no signs of past water damage*; some nail rust but integrity still fair; floorboard-to-joist connection has some but little movement; small degree of timber wear surrounding nails	0.75	0.90
D3 - Poor	Considerable borer; water damage evident*; nail rust extensive; significant timber degradation surrounding nails; floorboard joist connection appears loose and able to wobble	0.30	0.70

(*): Degradation process is assumed to be no longer active, the biotic cause of degradation is assumed to be no longer present

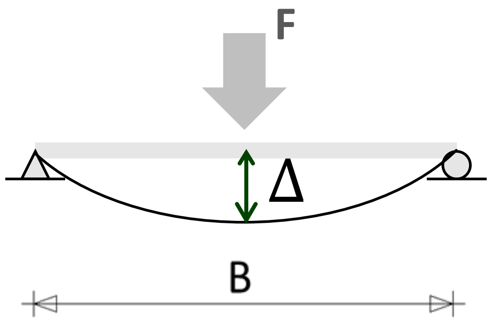
In-plane stiffness of timber diaphragms



Timber diaphragms are «assemblies» with many structural components



It is quite common to consider timber diaphragms as "ideal diaphragms" made of a homogeneous fictitious material



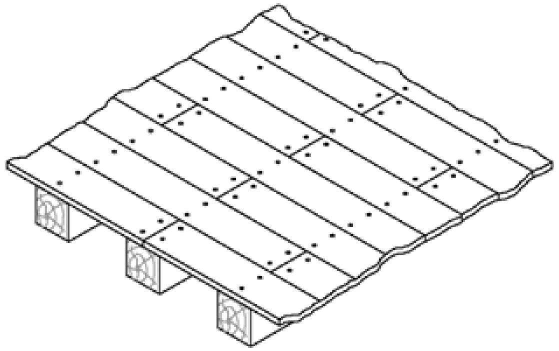
$$\Delta = \frac{F \cdot B^3}{48 \cdot E \cdot J} + \chi \frac{F \cdot B}{4 \cdot G \cdot (Lt)}$$

Beam analogy

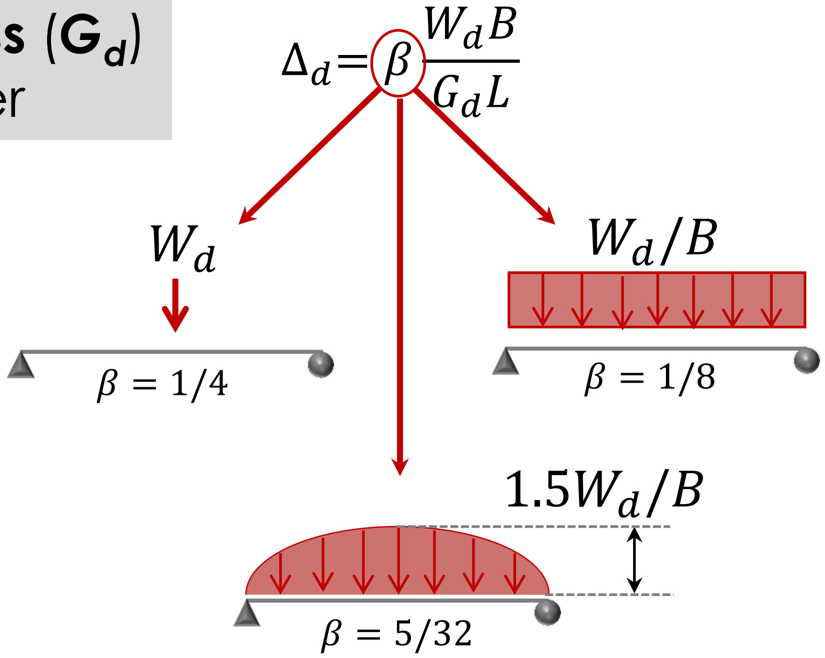
CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

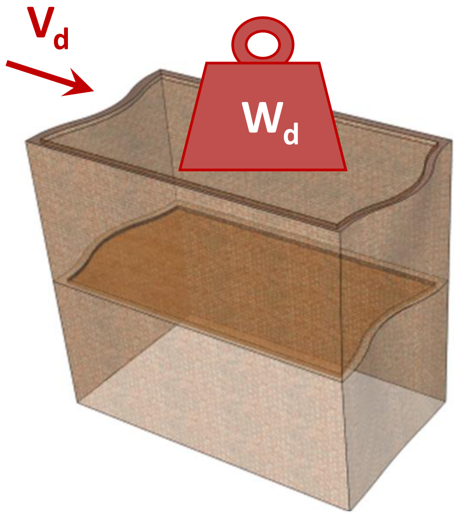
In-plane stiffness of timber diaphragms

The diaphragm is considered as a beam subject to
shear deformability only



The **equivalent shear stiffness** (**G_d**) becomes the key parameter

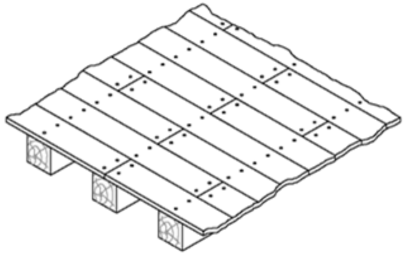




CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

$$G_{d0,eff} = \varphi \cdot \alpha_m \cdot \frac{A_n}{A} \cdot G_{d,0}$$



Single straight sheathing

Table 10.7 *Reference values for the equivalent shear stiffness,* $G_{d,0}$ [kN/m]**

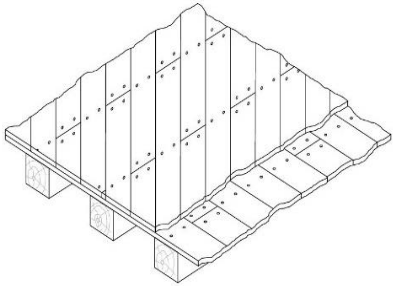
	No retrofit	Retrofit			
		(a)	(b)	(e)	(f)***
Single straight sheathing	150	3000	1800	3000	3000
Single straight sheathing (SQ joists)*	400	3600	2400	4100	3800

* When the diaphragm is loaded in the direction perpendicular to the joists.

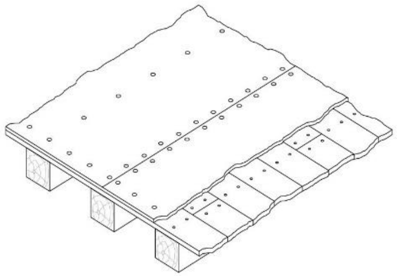
** Given values can be considered as reference values. Background information is provided in Annex D2

*** This retrofit strategy, that is mainy intended for improving diaphragm out-of plane performance, requires squat joists (SQ) in order to be effective.

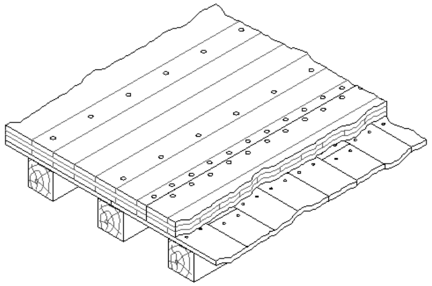
WOOD-BASED RETROFIT SOLUTIONS



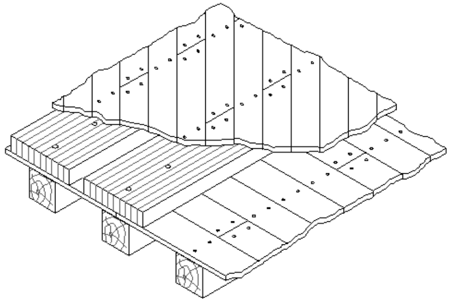
(a) Additional sheathing (diagonal floorboards)



(b) Structural wood-based panel overlay



(e) Additional CLT or LVL panels

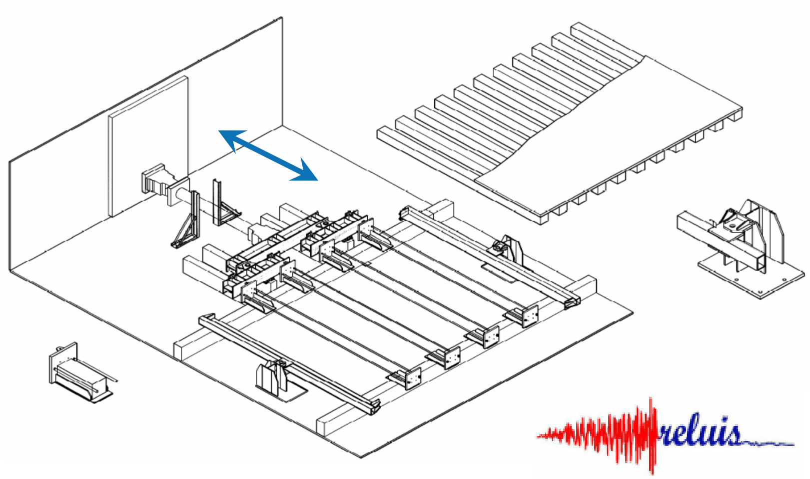


(f) Timber planks and additional floorboard overlay

CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

Specimen size: 5 m × 4 m
Loading direction: parallel to the joists



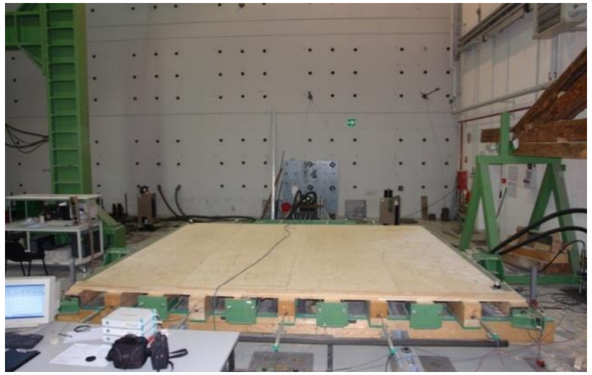
Single straight sheathing

Additional diagonal sheathing

Steel / CFRP strips

RC slab

Plywood overlay



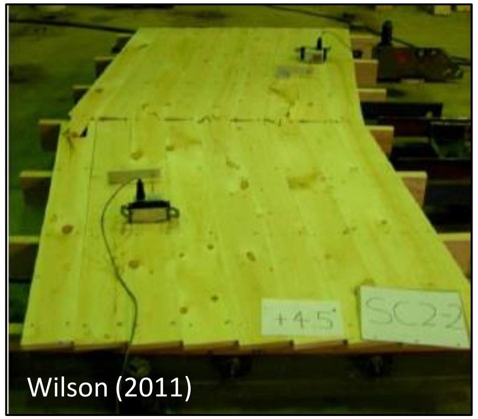
CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

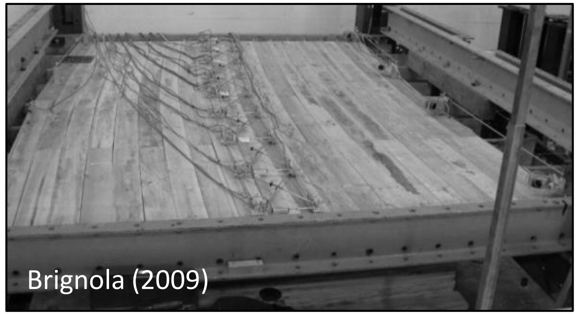
In-plane stiffness of timber diaphragms

- Different geometries (size, aspect ratio)
- Laboratory-built specimens (onsite testing is quite rare)
- Loading direction (parallel to the joists, perpendicular to the joists)
- Strengthening details (panel thickness, fastener spacing and type)

Quite different $G_{d,0}$ values!


Modena, Valluzzi et al. (2008)


Wilson (2011)


Brignola (2009)

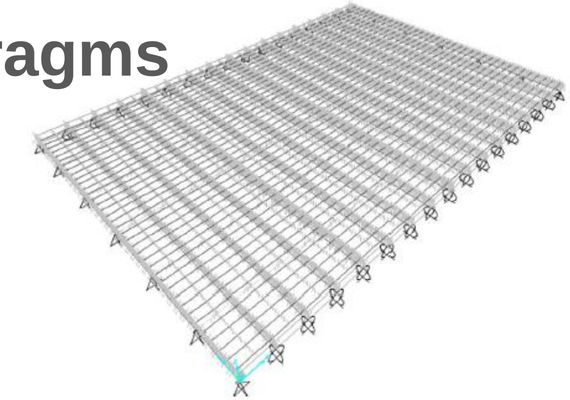

Giongo et al. (2012)

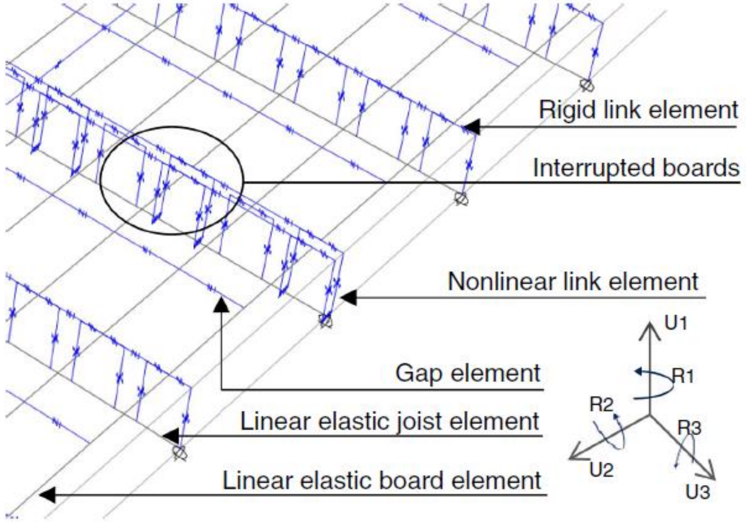

Gubana & Melotto (2018)

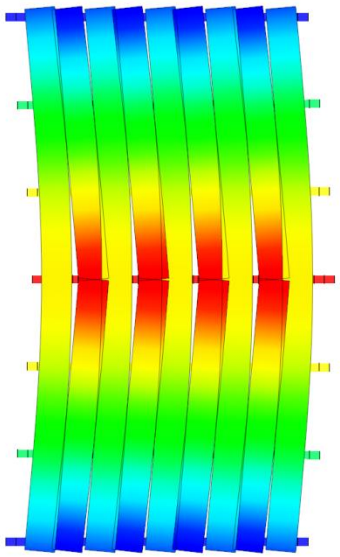
CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

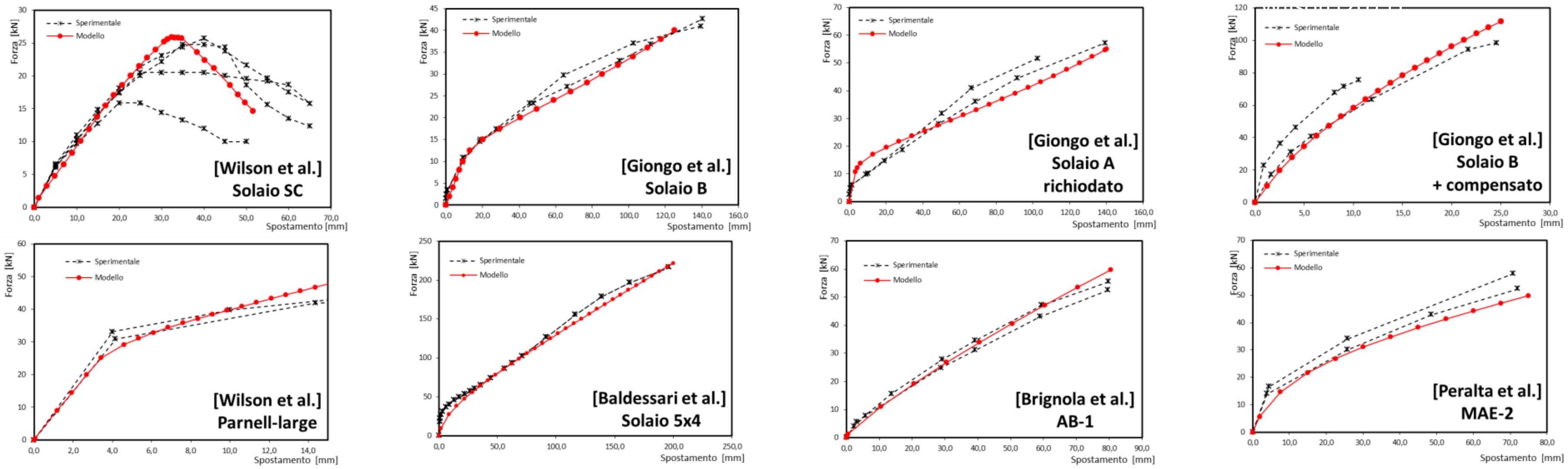
It is necessary to find "shared interpretation keys" which allow defining rules and provisions of general validity.







NUMERIC MODELLING



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

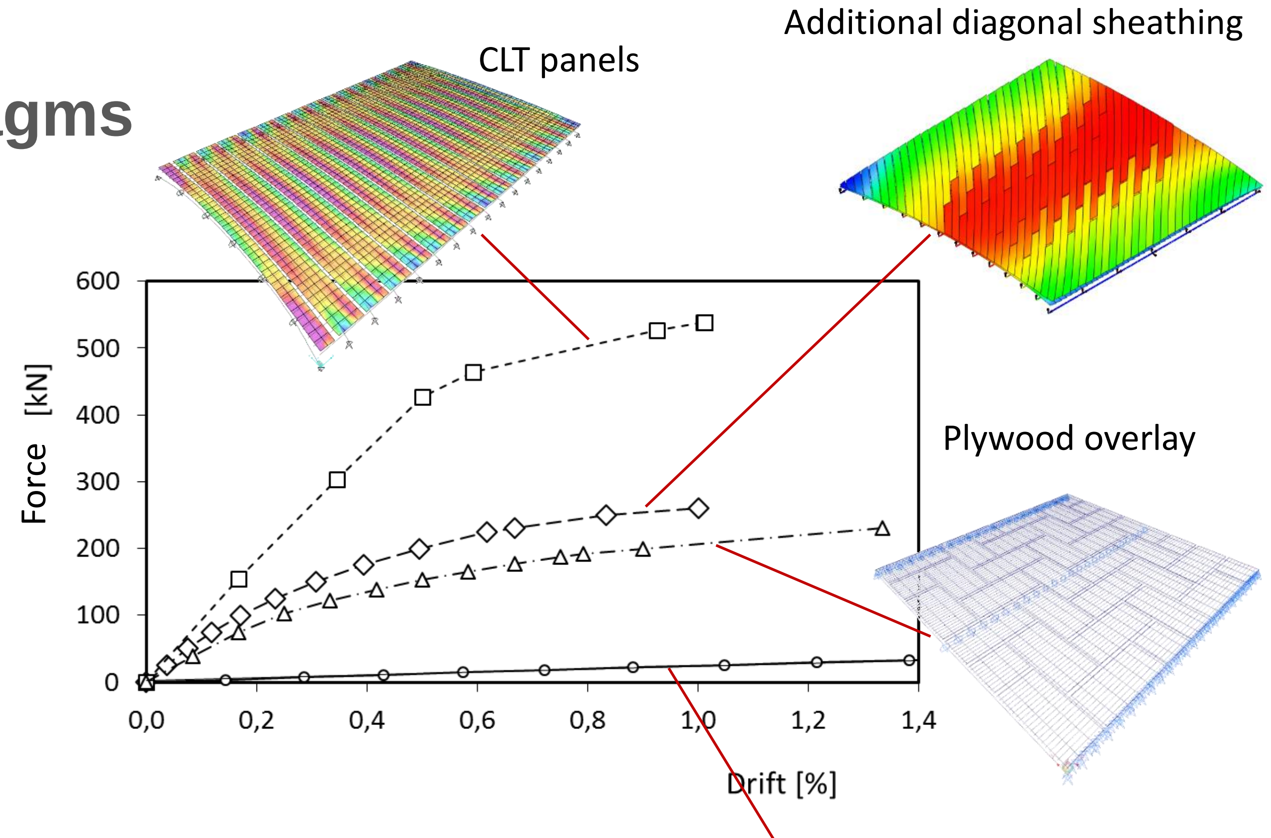
In-plane stiffness of timber diaphragms

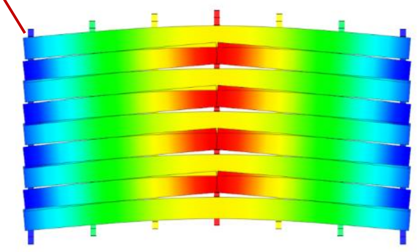
It is necessary to find "shared interpretation keys" which allow defining rules and provisions of general validity.

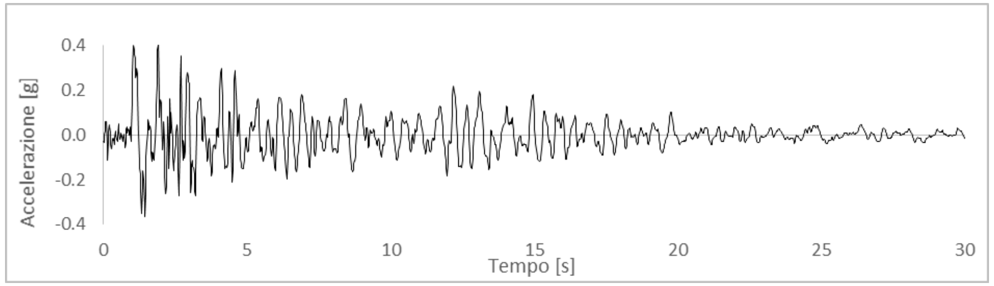
Parametric study focused on:

- ✓ Aspect ratio
- ✓ Scale factor (i.e., size)
- ✓ Loading direction

- Different modelling approaches
- Non-linear static analyses
- Non-linear dynamic analyses







CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

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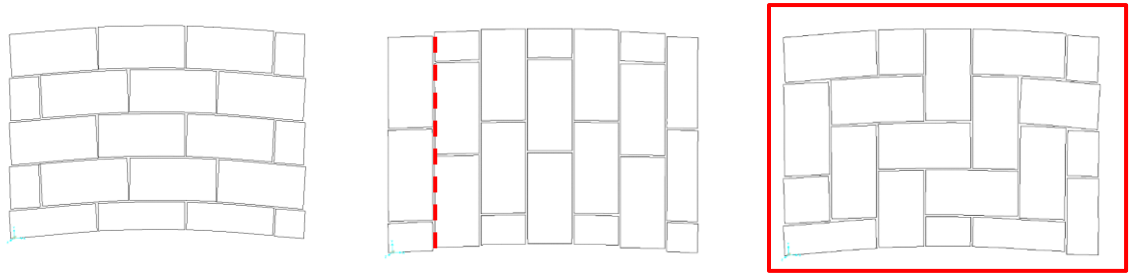
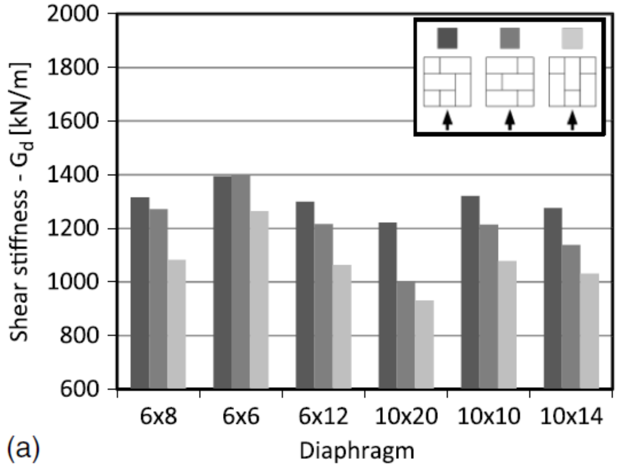
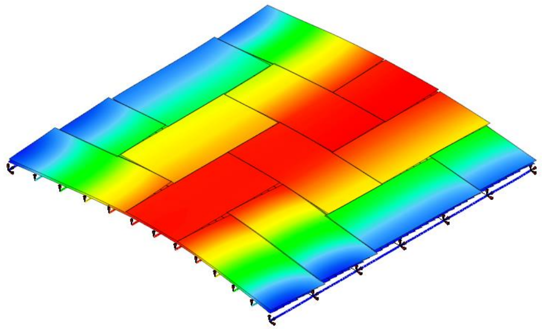
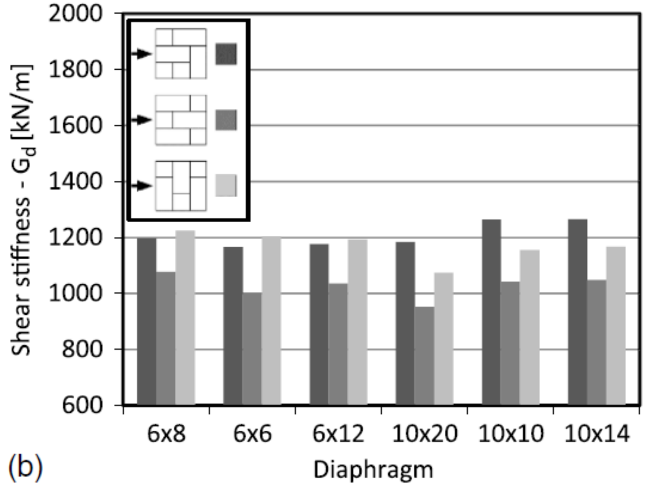


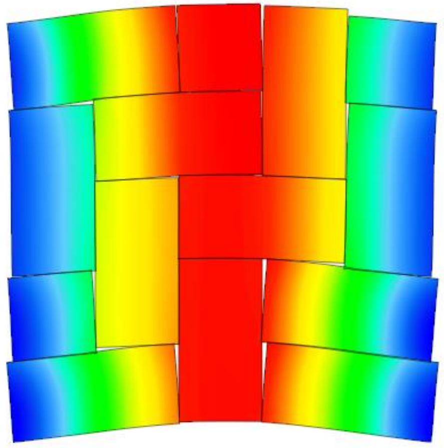


(a)





(b)



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

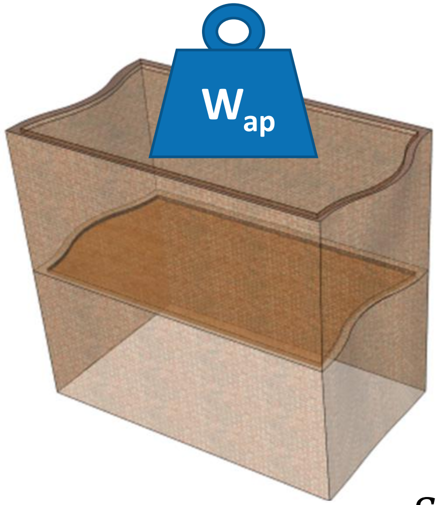
$$S_d(T_{ap}) = \alpha \cdot S \cdot \left(\frac{3 \cdot \left(1 + \frac{Z}{H}\right)}{1 + \left(1 - \frac{T_{ap}}{T_1}\right)^2} - 0.5 \right)$$

EN 1998-1:2005

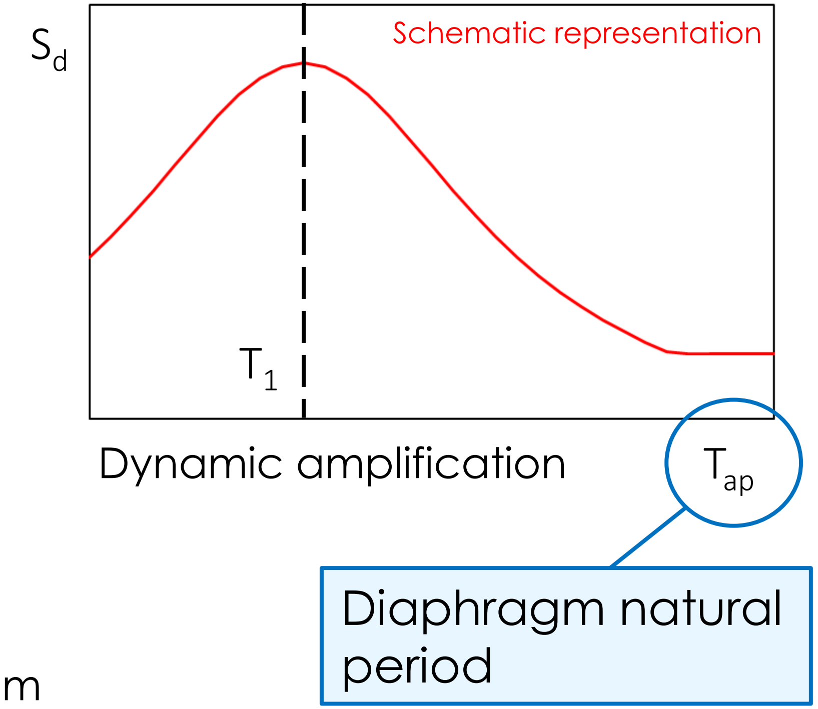
In-plane stiffness of timber diaphragms

$S_d(T_{ap}) = f\ (T_1, \dots)$ ➡ **prEN 1998-1-2:2022 (E)**

The total inertia force acting on the diaphragm



$$F_a = (S_d \cdot m_{ap} \cdot g)/q_{ap}$$



$S_d = S_{ap}$ is the diaphragm spectral acceleration

q_{ap} is the behaviour factor

$m_{ap} \cdot g = W_{ap}$ is the seismic weight of the diaphragm

CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

How do we calculate the diaphragm oscillating period T_{ap} ?

$$T_{ap} = \alpha_T \cdot \left(\frac{m_{ap} g \cdot L_a}{1000 \cdot G_{d0,eff} \cdot B} \right)^{0.5}$$

RAYLEIGH'S QUOTIENT

$\alpha_T = 0{,}63$ Modal shape from parabolic loading, uniform mass distribution

$\alpha_T = 0{,}64$ Modal shape from uniform loading, uniform mass distribution

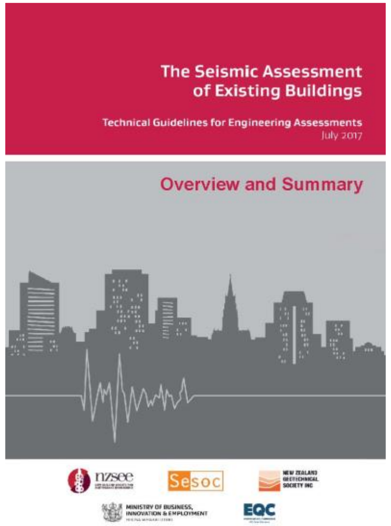
$\boldsymbol{\alpha_T = 0,70}$ One third of total mass lumped at each diaphragm third-point

Depends on the modal shape and on the mass distribution

is the period T_{ap} realistic??

Wilson, A., Quenneville, P., and Ingham, J. (2013). "Natural period and seismic idealization of flexible timber diaphragms." Earthquake Spectra, 29(3), 1003–1019.

NZSEE 2017



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

Diaphragm oscillating period |Snap-back Testing

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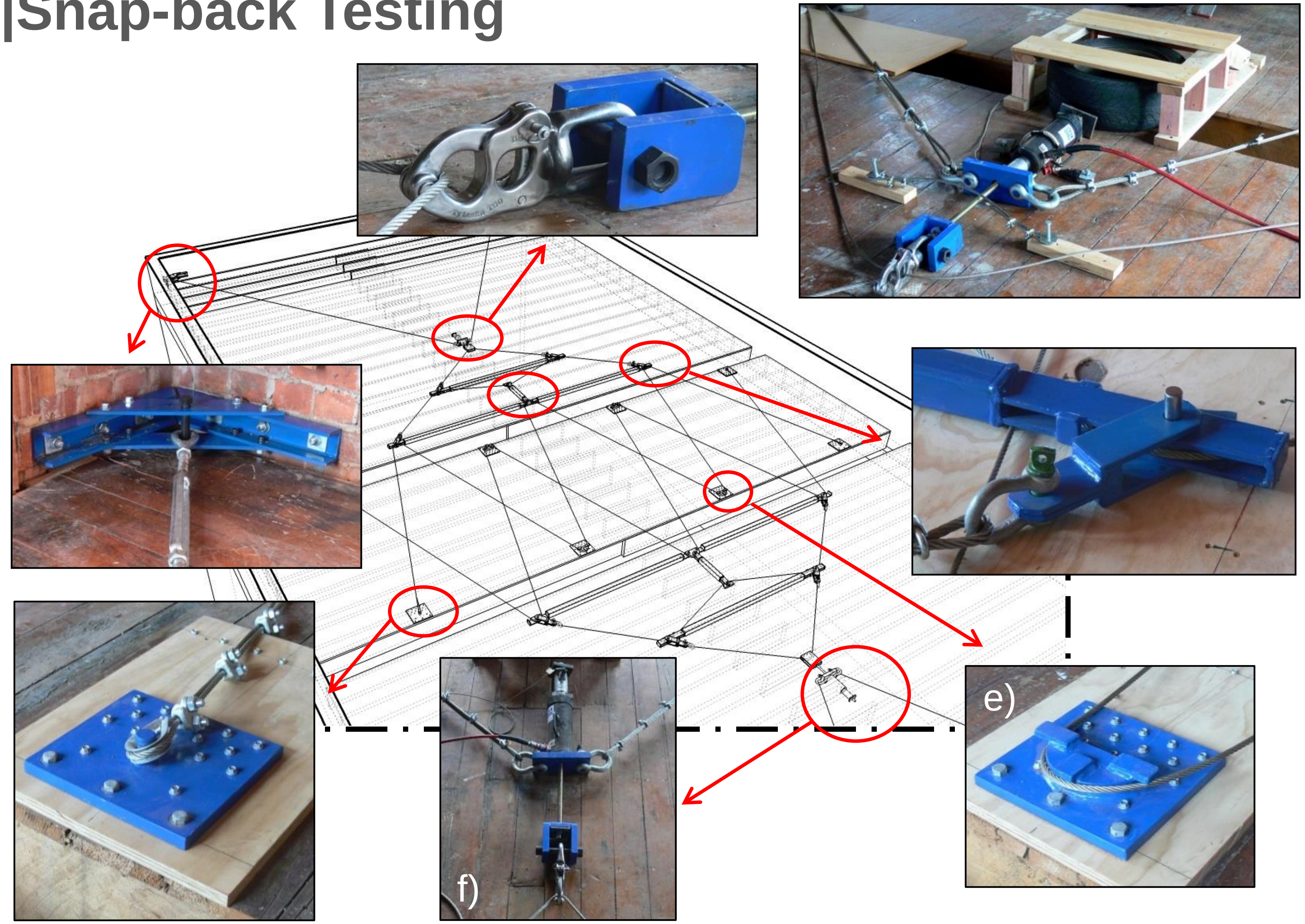
Dipartimento di Ingegneria Civile e Ambientale



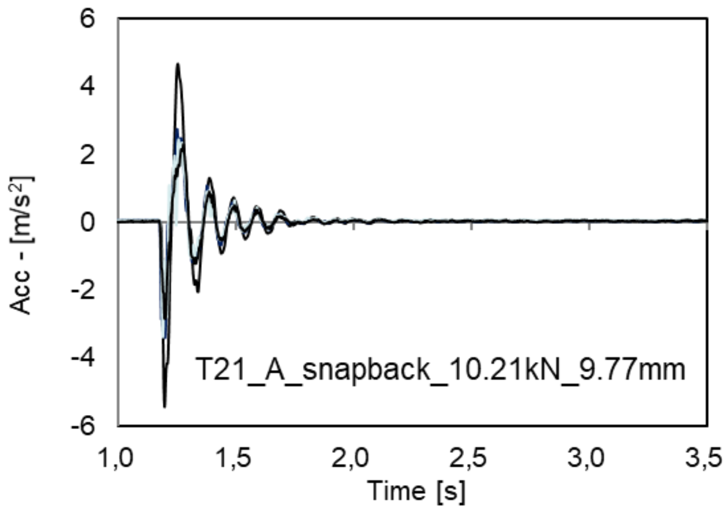
Chapter 10 | Specific rules for timber buildings

Diaphragm oscillating period |Snap-back Testing

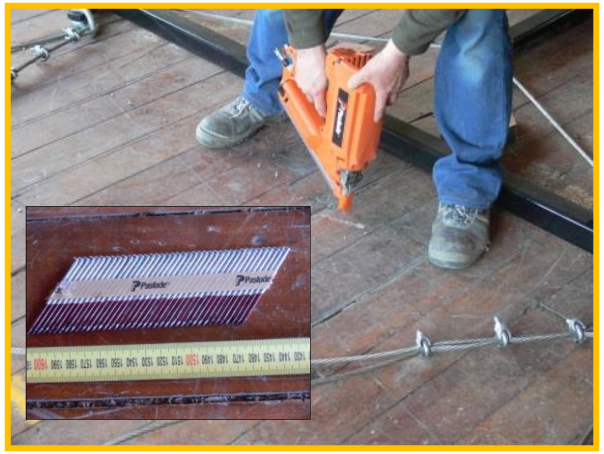
$$T_{ap} = 0.63\sqrt{\frac{F_d L}{G_d B}} \cdot \theta$$

$$\theta = \sqrt{\frac{pBL}{F_d}}$$

F_d Total force on the diaphragm



Experimental data			Analytical value	
Test n°	T [s]	Disp. [mm]	T [s]	Err. [%]
T4_A	0.12	10.00	0.12	1%
T6_A	0.25	61.82	0.22	12%
T7_A	0.25	60.68	0.22	12%
T11_A	0.37	131,12	0.35	6%
T15_A	0.41	152,55	0.38	7%
T19_A	0.34	120,97	0.33	3%
T23_A	0.34	101,55	0.33	1%
T27_B	0.45	157,15	0.49	9%
T29_B	0.45	152,89	0.51	13%
T36_B	0.10	10,09	0.12	19%
T44_C	0.17	35,83	0.16	3%



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

$$G_{d0,eff} = \varphi \cdot \alpha_m \cdot \frac{A_n}{A} \cdot G_{d,0}$$

It takes into account the presence of openings

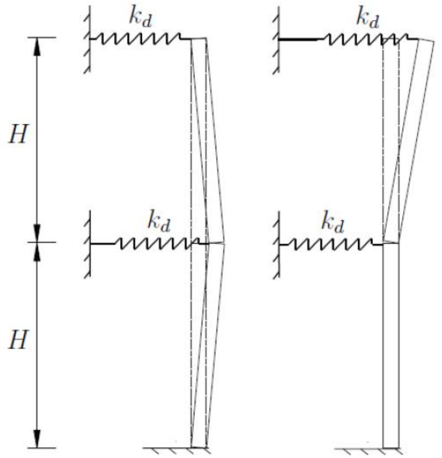
A_n is the diaphragm net area
A is the diaphragm gross area

It takes into account the stiffness of the face-loaded walls

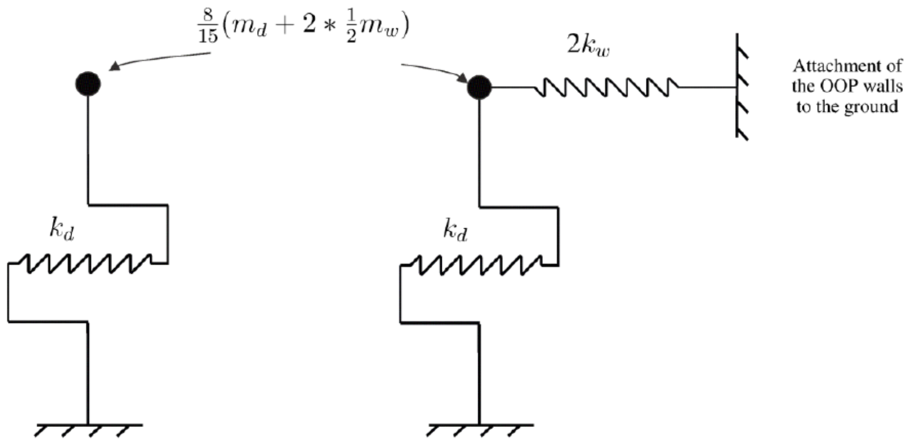
$$\alpha_m = 1 + \left(\frac{t_i^3}{h_i^3} + \frac{t_s^3}{h_s^3}\right) \frac{L_a}{B}^2 \frac{E_m}{G_{d,0}} \frac{A}{A_n}$$

Giongo I., Wilson A., Dizhur D., Derakhshan H., Tomasi R., Griffith M. C., Quenneville P., Ingham J. M., "*Detailed seismic assessment and improvement procedure for vintage flexible timber diaphragms*", BULLETIN OF THE NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING, Vol. 47, No. 2, June 2014


Displacement incompatibility between diaphragm and URM end walls.



(a) Middle-storey (b) Top-storey



(a) Excluding out-of-plane wall stiffness (b) Including out-of-plane wall stiffness

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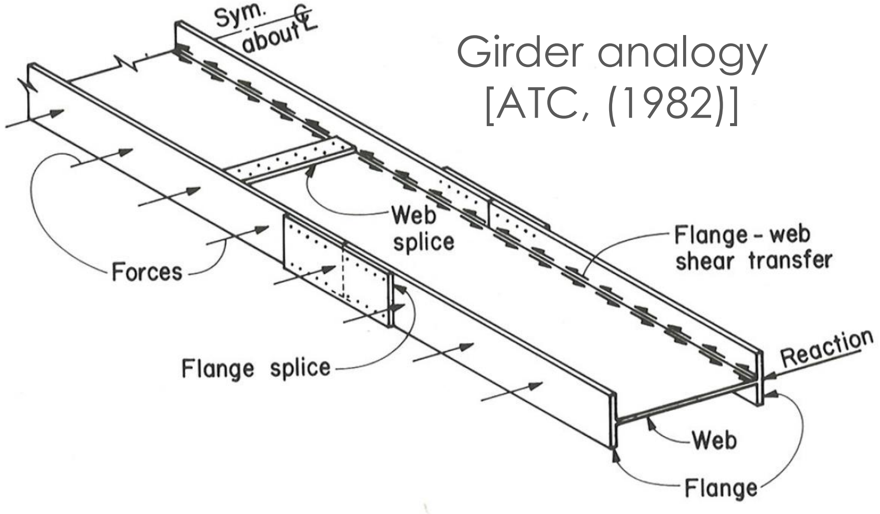
CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

$$G_{d0,eff} = \varphi \cdot \alpha_m \cdot \frac{A_n}{A} \cdot G_{d,0}$$

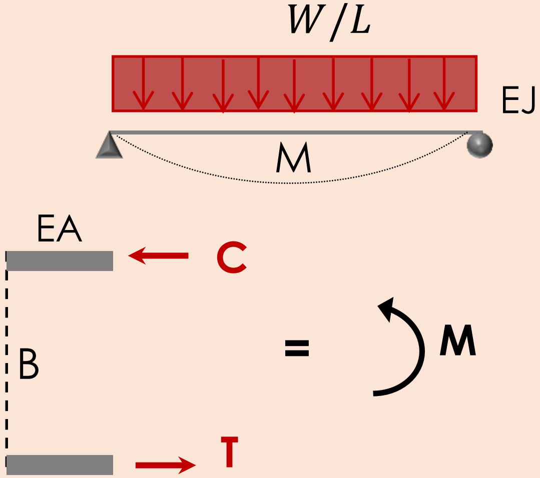


Girder analogy [ATC, (1982)]

10.8.2.2. (1) The influence of **perimeter chords** on the diaphragm in-plane stiffness depends on the type of diaphragms and on the mechanical properties of the chord members and of the chord-to-diaphragm connection.

NOTE For diaphragms that do not exhibit a clear flexural response, such as single straight sheathed diaphragms, the chord contribution is usually limited, and it is related to the bending stiffness of the chord members. In cases where a more **pronounced diaphragm flexural response is expected**, the chord axial stiffness is engaged (depending on the stiffness of the chord-to-diaphragm connection) and the perimeter chords may act similarly to the flanges of a girder.

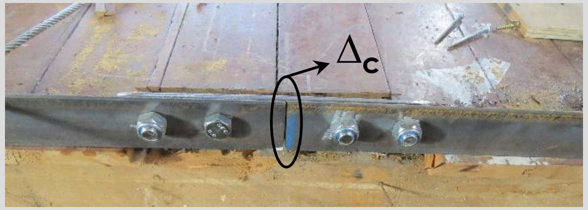
Diaphragm **chord** (flange) contribution



Diaphragm yield displ. [ASCE 41-17]

$$\Delta_y = \frac{5 v_y L^3}{8EAB} + \frac{v_y L}{4Gt} + \frac{\sum(\Delta_c X)}{2B} + \alpha L e_n$$

Chord-splice deformability



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

In-plane stiffness of timber diaphragms

$$G_{d0,eff} = \varphi \cdot \alpha_m \cdot \frac{A_n}{A} \cdot G_{d,0}$$

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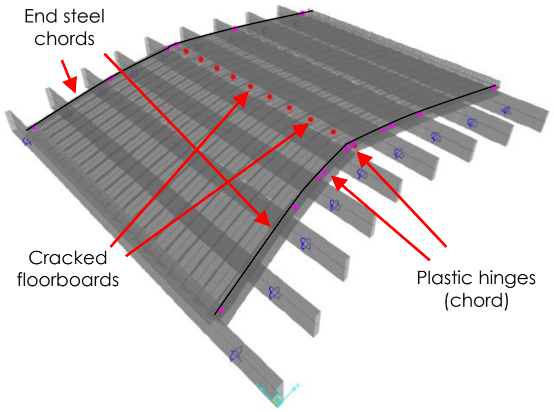
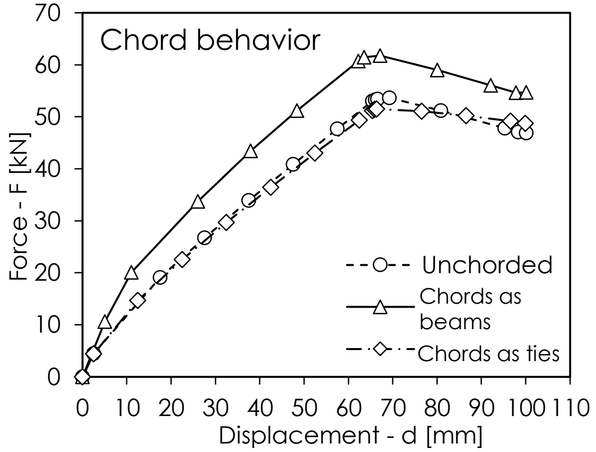
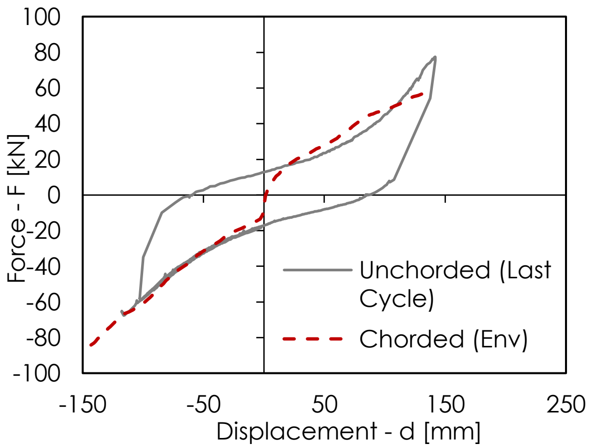


Numerical proof-check



Experimental evidence [Rizzi et al. 2020]



CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

Diaphragm verification | Resistance Check

$$v_{Ed} \leq v_{Rd}$$

Unit shear force at the diaphragm support edges

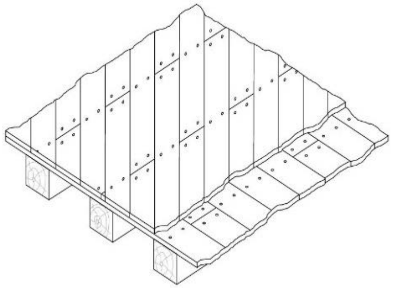
$$v_{Ed} = \frac{F_a}{2B}$$

Table 10.4 *Acceptance criteria in terms of unit shear strength v_R [kN/m]***

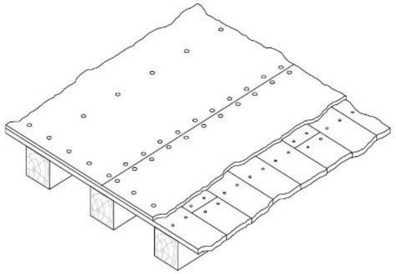
	No retrofit	Type of retrofit			
		(a)	(b)	(e)	(f)
Parallel to joists	3	30	25	40	30
Perpendicular to joists	5*	45	25	45	40

* In case of SQ joists, diaphragm shear strength in the direction perpendicular to the joists, can be significantly higher than the v_R value reported in the table.

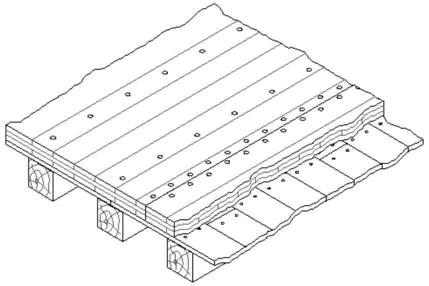
** Given values can be considered as mean reference values.



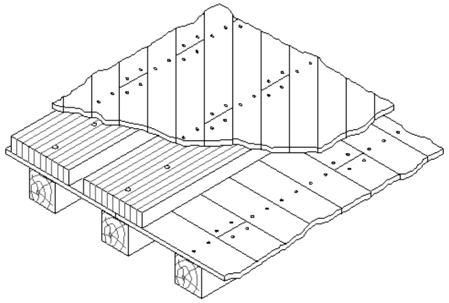
(a) Additional sheathing (diagonal floorboards)



(b) Structural wood-based panel overlay



(e) Additional CLT or LVL panels



(f) Timber planks and additional floorboard overlay

Chapter 10 | Specific rules for timber buildings

Diaphragm verification | Deformation Check

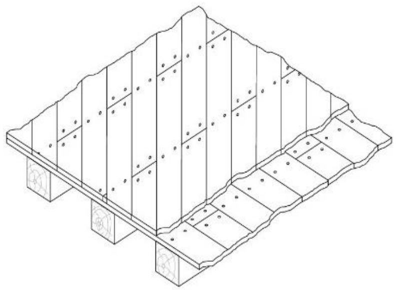
$$d_r = \frac{2 \cdot \Delta_d}{L_a} \cdot 100 \leq d_{r,max}$$

Displacement demand

$$\Delta_d = 1{,}25 \cdot 10^{-3} \cdot \mu_d \cdot S_d\left(T_{ap}\right) \cdot \frac{L_a \cdot m_{ap}}{B \cdot G_{d,eff}}$$

***Table 10.4** Acceptance criteria in terms of drift ratios $d_{r,max}$ [%]*

	No retrofit	Type of retrofit			
		(a)	(b)	(e)	(f)
Near Collapse (NC)	6.0%	2.1%	1.6%	1.5%	2.1%
Significant Damage (SD)	4.0%	1.5%	1.2%	1.1%	1.5%
Damage Limitation (DL)	2.5%	0.8%	0.7%	0.6%	0.8%



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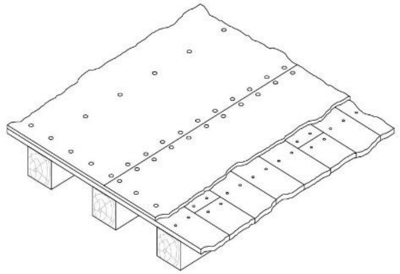
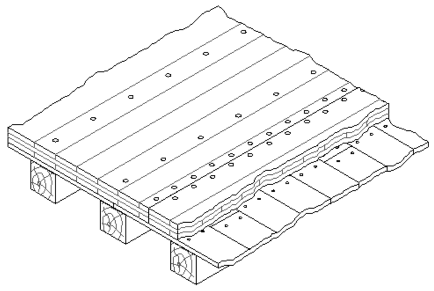
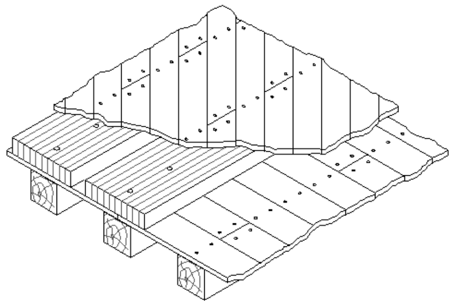


(b) Structural wood-based panel overlay



(e) Additional CLT or LVL panels



(f) Timber planks and additional floorboard overlay

CHAPTER 10 | SPECIFIC RULES FOR TIMBER BUILDINGS

Diaphragm verification | Deformation Check

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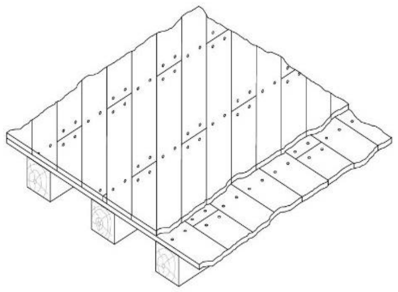
$$\Delta_d = 1{,}25 \cdot 10^{-3} \cdot \mu_d \cdot S_d\left(T_{ap}\right) \cdot \frac{L_a \cdot m_{ap}}{B \cdot G_{d,eff}}$$

$$\mu_d = \frac{q_{ap}^2 + 1}{2}$$

Ductility factor as per Newmark and Hall's relation



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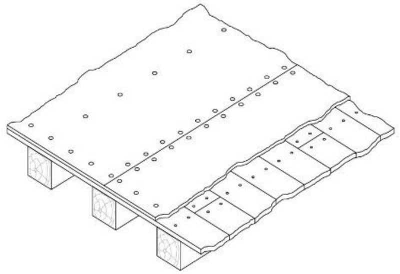

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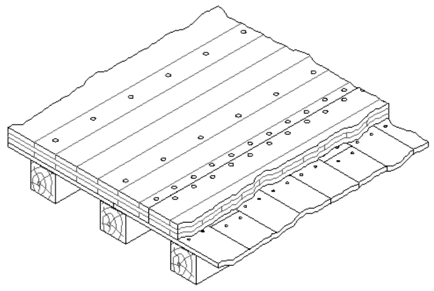
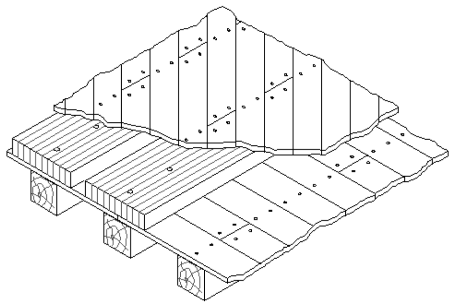


(e) Additional CLT or LVL panels



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Chapter 10 | Specific rules for timber buildings

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$$\mu_d = \frac{q_{ap}^2 + 1}{2}$$

Ductility factor as per Newmark's relation

q_{ap} Diaphragm behaviour factor (1,5 for all diaphragm type)

Nonlinear Static/Dynamic Study (q_{ap})

Diaphragm types

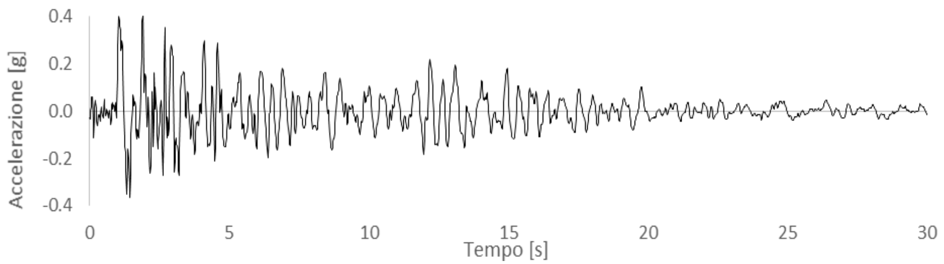
- Single straight sheathing
- Plywood overlay over straight sheathing
- Diagonal sheathing over straight sheathing
- CLT panels over straight sheathing

Geometries

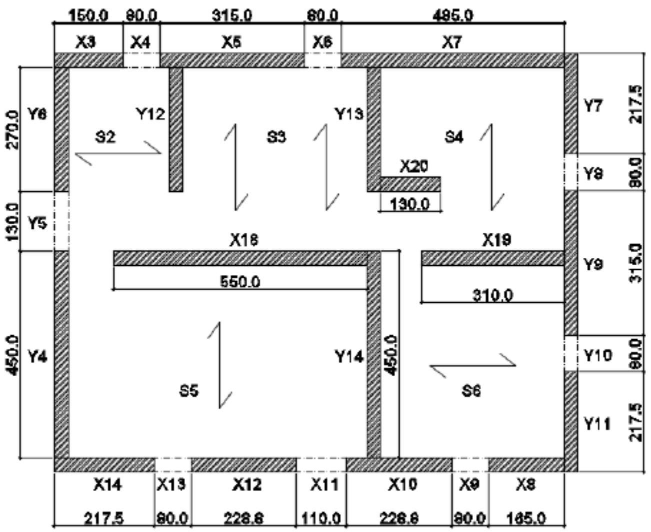
ID	L [m]	B [m]
6x8	6	8
6x6	6	6
6x12	6	12
4x4	4	4
4x8	4	8

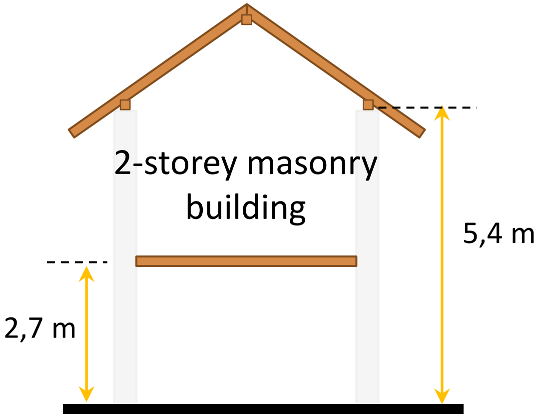
Ground motions

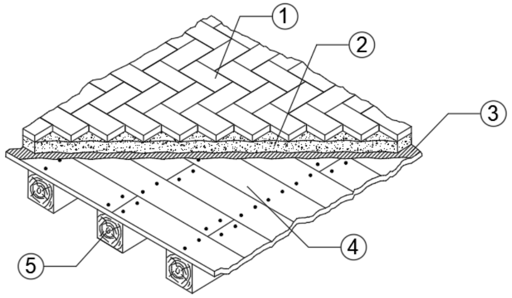
- Two sets of natural accelerograms (PGA=0.2g & PGA=0.4g)
- Each set comprised 7 accelerograms (total of 14)
- Two loading directions (slender and squat joist scenarios)



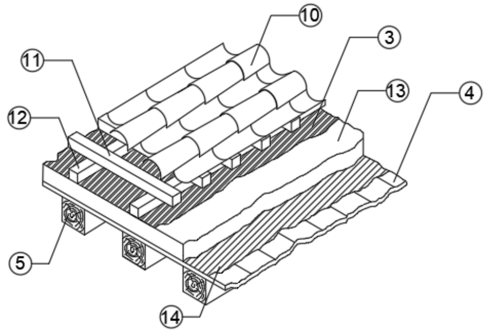
Worked example







Timber floor



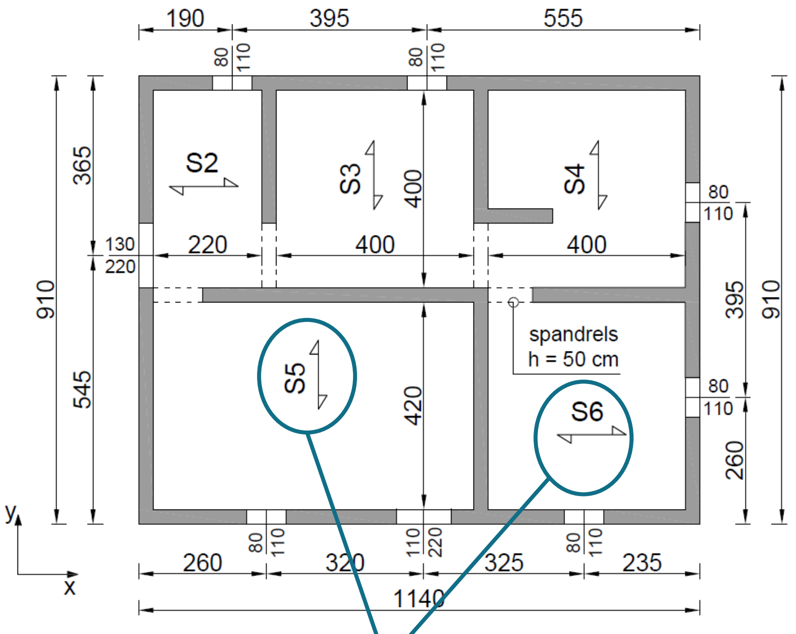
Timber roof

1) Terracotta tiles
2) Screed
3) Waterproof breathable membrane
4) Wood decking
5) Timber joist

10) Roof tiles
11) Timber lath for tile support
12) Timber lath for ventilation
13) Wood fibre insulation
14) Vapour barrier

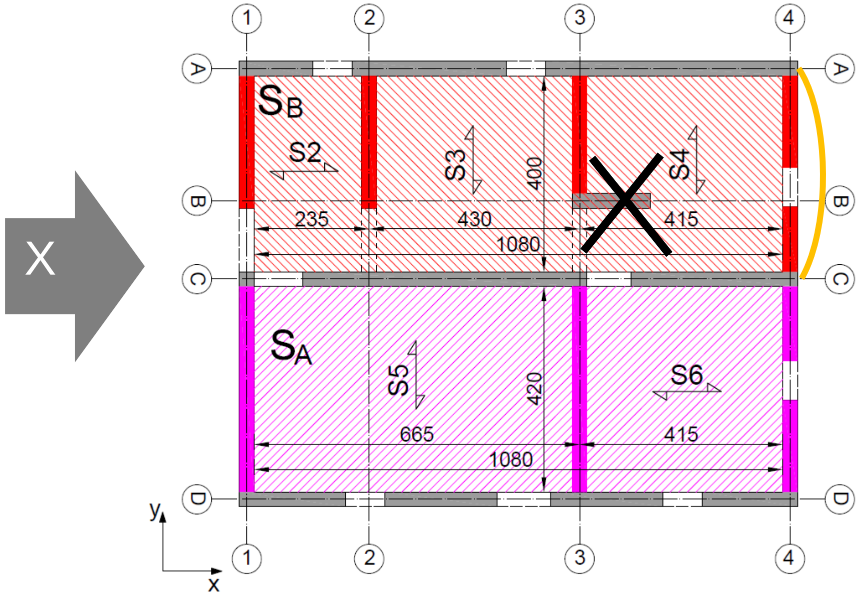
Giongo I., Rizzi E., Piazza M., "Seismic assessment of timber diaphragms according to the new draft of EN1998-3",6th International Conference on Structural Health Assessment of Timber Structures, 7-9 September 2022, Prague

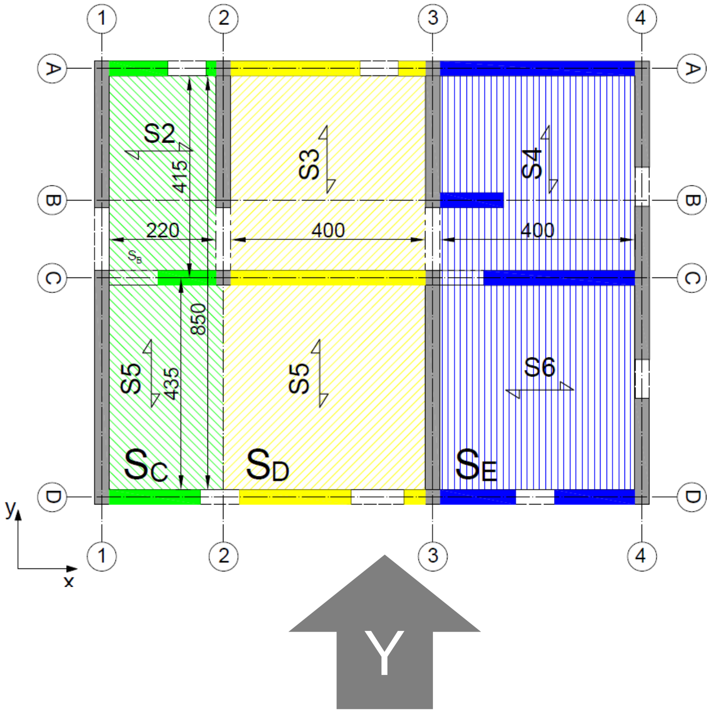
Worked example



Due to the wall layout, diaphragms (S1 to S6) have different joist orientation

Earthquake loading directions





$$G_{d,0} = \frac{\sum_i G_{d,0}^i \cdot B_i}{\sum_i B_i}$$

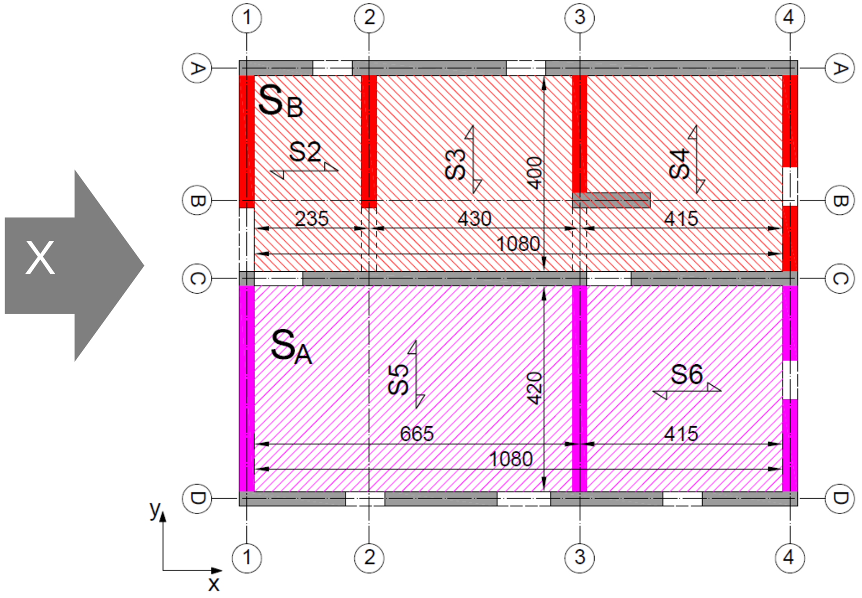
- Equivalent diaphragms (S_A, S_B, S_C, S_D, S_E)
- Deformation compatibility assumption
- Walls parallel to the seismic force provide full restraint to in-plane deformation (if > 25% equivalent diaphragm length)

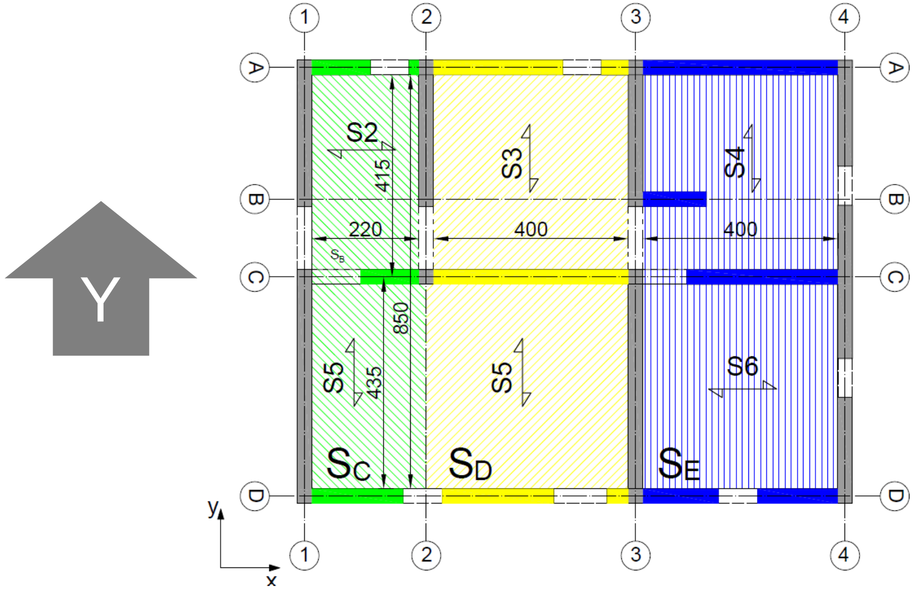
Worked example

EQUIVALENT FLOOR-DIAPHRAGMS

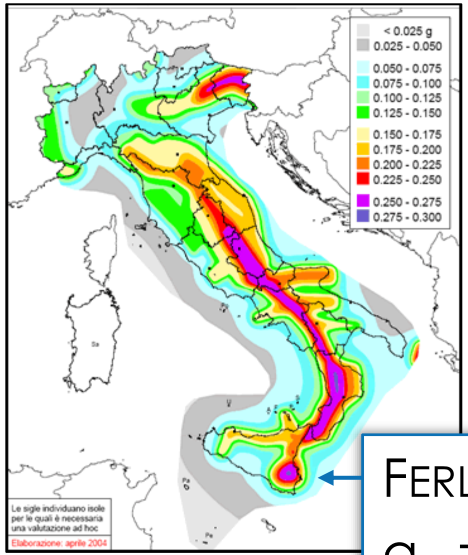
		Floor bay	Orientation*	$G_{d,0}$ - floor bay [kN/m]	B [m]	$G_{d,0}$ – equiv. diaph. [kN/m]
X	S_A	S_5	90	400	6.65	304
		S_6	0	150	4.15	
	S_B	S_2	0	150	2.35	**346**
		S_3	90	400	4.30	
		S_4	90	400	4.15	
Y	S_C	S_2	90	400	4.15	272
		S_5	0	150	4.35	
	S_D	S_3	0	150	4.15	**150**
		S_5	0	150	4.35	
	S_E	S_4	0	150	4.15	278
		S_6	90	400	4.35	

* Joist orientation: 0 – parallel to the seismic load; 90 – perpendicular to the seismic load

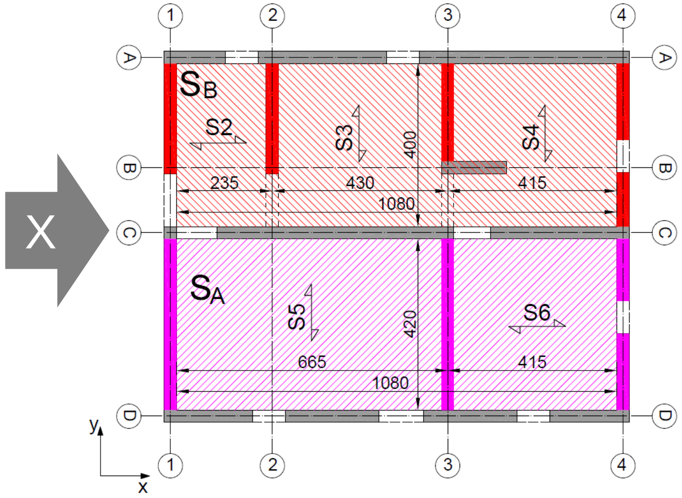


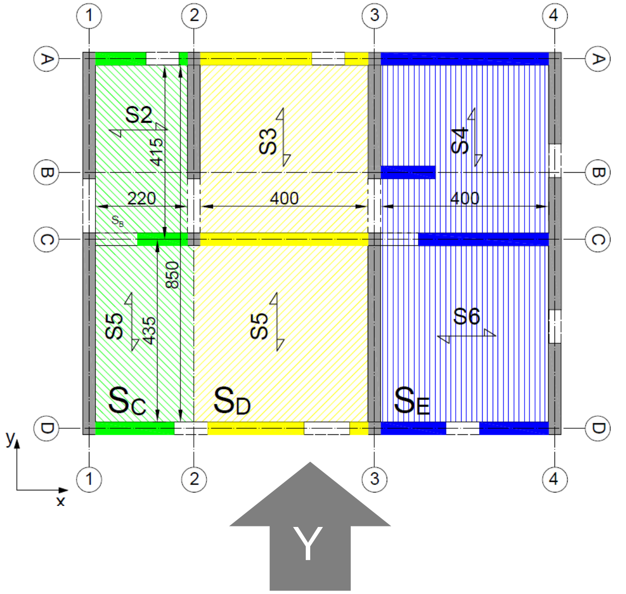


Worked example



FERLA (IT)
a_g = 0,28 g
T_R = 475 years



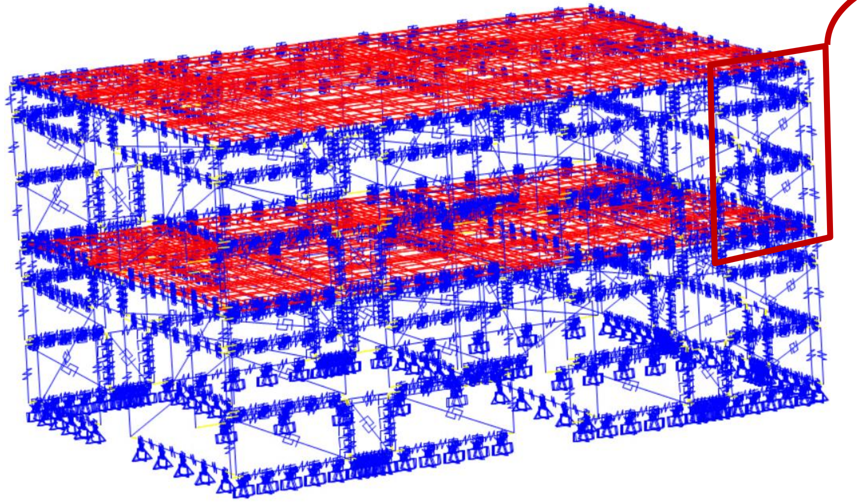


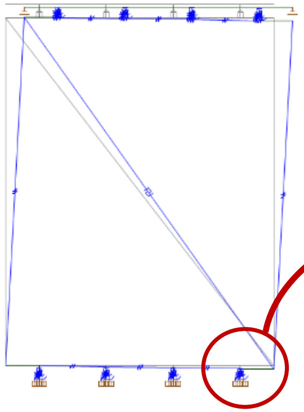
- Health condition: "*D2 – Fair*" (φ = 0,75)
- Mass of perpendicular walls added to the tributary mass of the equiv. diaphragms
- $T_1 = 0.177\ s$

Fl. level		L_a [m]	B [m]	$G_{d,eff}$ [kN/m]	m_{ap} [kg]	T_{ap} [s]	F_a [kN]	Δ_d [mm]
1	S_A	4.2	10.8	233	32005	0.507	60.46	30.19
	S_B	4.0	10.8	**264**	30526	0.454	57.67	24.22
	S_C	2.2	8.5	206	13339	0.284	70.53	26.52
	S_D	4.0	8.5	**118**	26693	0.715	50.43	60.05
	S_E	4.0	8.5	214	29164	0.555	55.10	36.20

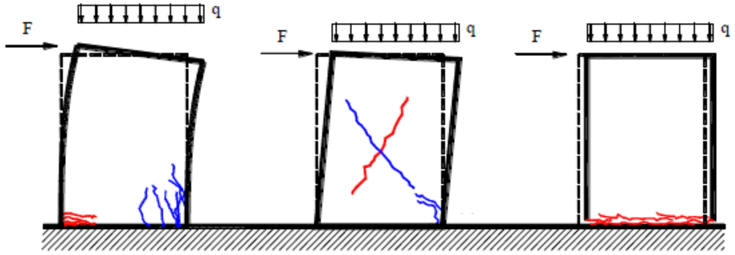
Worked example

COMPARISON WITH FE MODEL

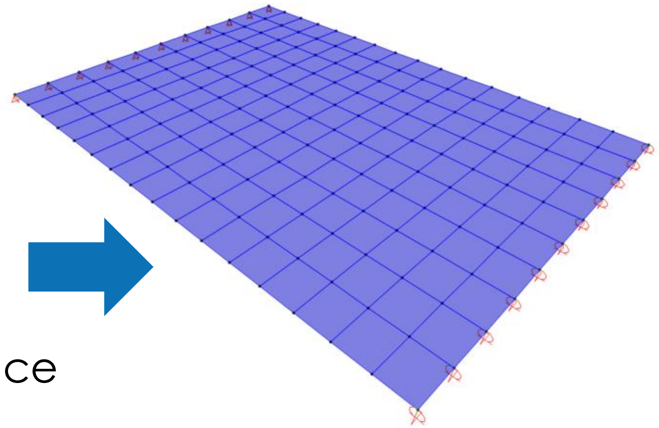


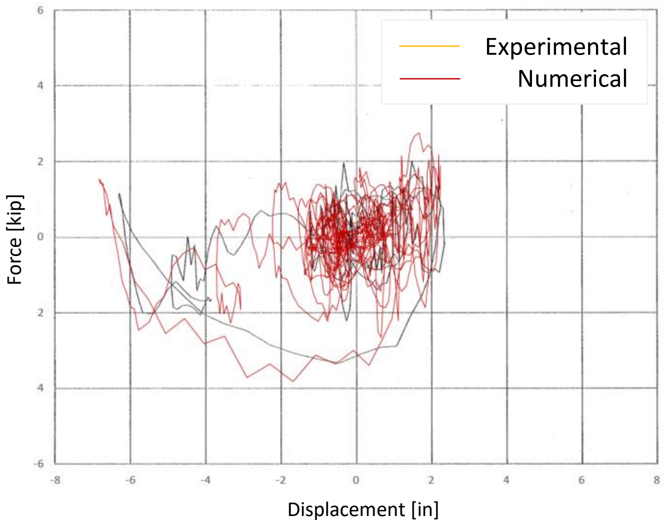


Set of non-linear link elements for reproducing masonry failure modes



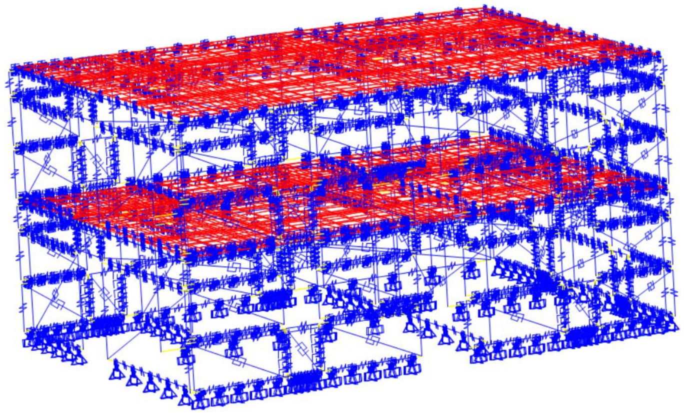
- Non-linear Finite Element modelling
- Software SAP2000
- Diaphragms modelled using orthotropic shell elements calibrated on NLTA
- Comparison was made at the performance point

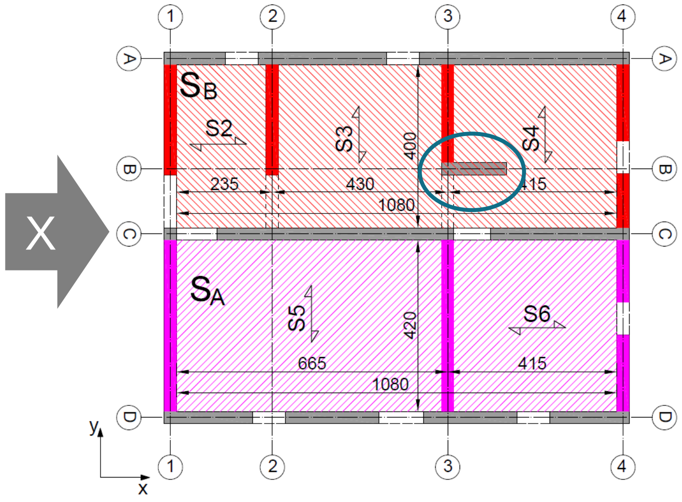




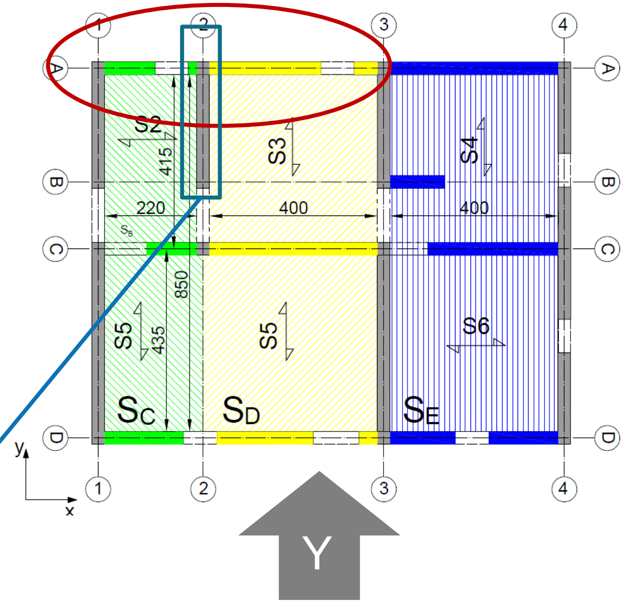
Worked example

Comparison with FE model

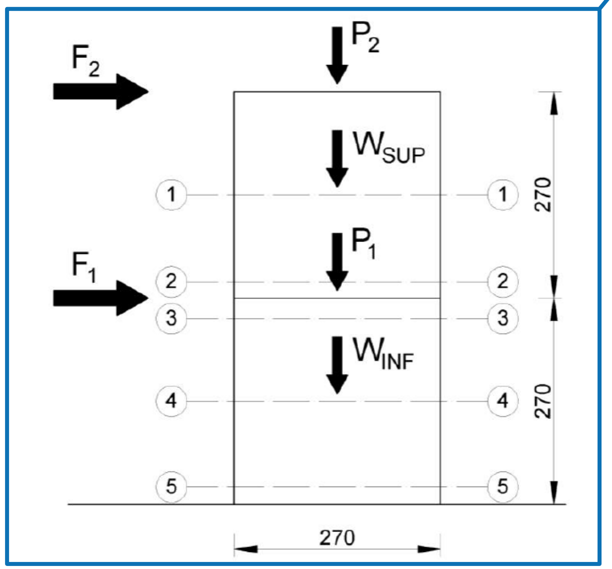




Large underestimation!



- Deformation difference on average ≈ < 35%
- General tendency to overestimate the FE deformation (e.g. for S_B)
- Large difference for S_C and S_D

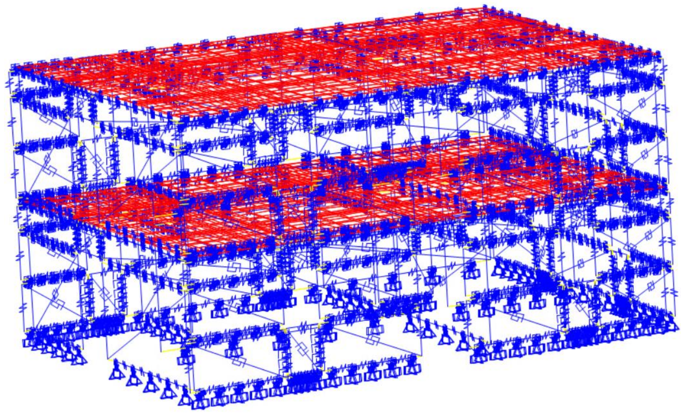


$$e_{5-5} = \frac{M_{Ed}^{5-5}}{N_{Ed}^{5-5}} = \frac{434.19\ kNm}{120.79\ kN} = 3.60\ m$$

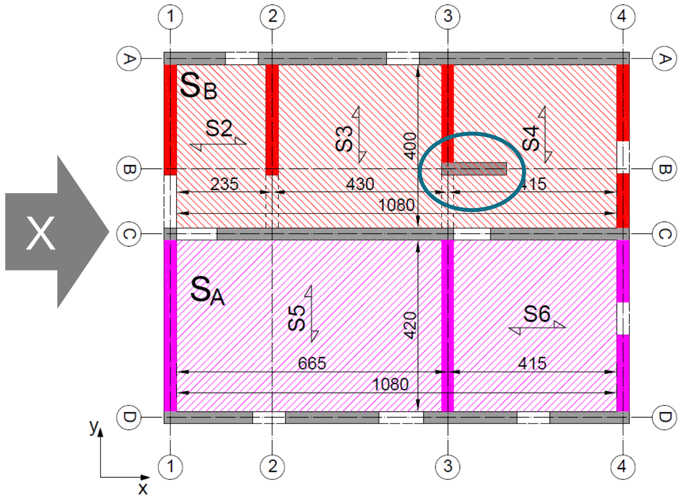
Wall section	N [kN]	V [kN]	M [kNm]
1-1	34,3	50,1	67,7
2-2	58,6	50,1	135,4
3-3	72,2	110,6	135,4
4-4	96,5	110,6	284,7
5-5	120,8	110,6	434,0

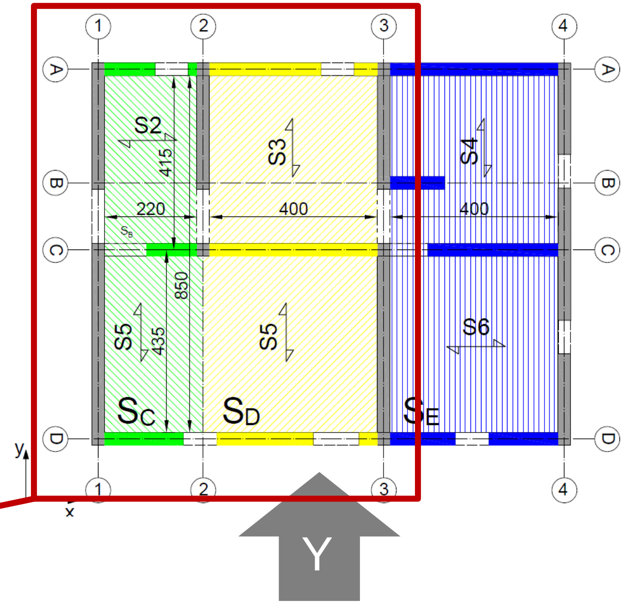
Worked example

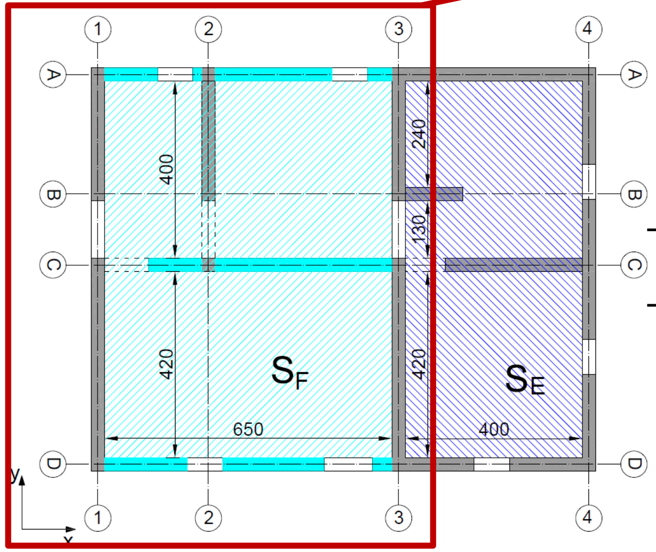
Comparison with FE model



- Deformation difference on average ≈ < 35%
- General tendency to overestimate the FE deformation (e.g. for S_B)
- Large difference for S_C and S_D
- S_F introduced to account for the failure of wall line 2 (smaller difference)





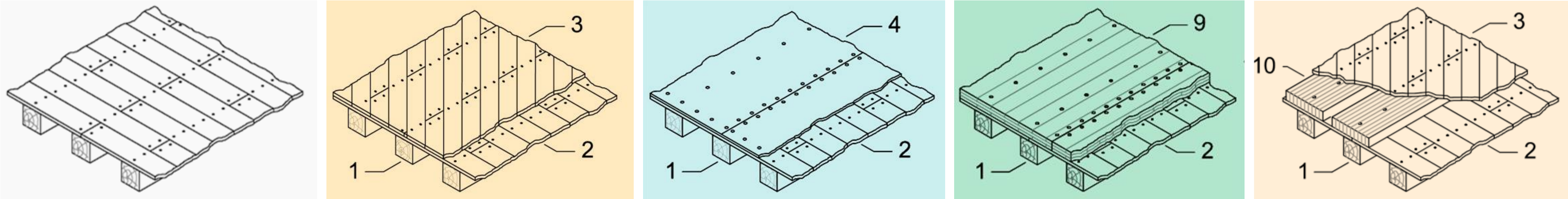


Floor	$G_{d,eff}$ [kN/m]	m_{ap} [kg]	T_{ap} [s]	F_a [kN]	Δ_d [mm]
S_F	160	40591	0.966	76.69	109.68

L_a [m]	B [m]	$G_{d,0}$ [kN/m]
6.50	8.50	193

Worked example

SAFETY CHECKS



DEFORMATION LIMITATION CHECKS

	As-B	Retrofit type			
		(a)	(b)	(e)	(f)
Floor ID	dr/dr_{cap}	dr/dr_{cap}	dr/dr_{cap}	dr/dr_{cap}	dr/dr_{cap}
S_A	0.36	0.28	0.57	0.34	0.27
S_B	0.30	0.25	0.52	0.30	0.24
S_E	0.45	0.34	0.68	0.42	0.33
S_F	0.84	0.46	0.69	0.62	0.46

FORCE LIMITATION CHECKS

		As-B	Retrofit type			
			(a)	(b)	(e)	(f)
Direction	Floor ID	v_{Ed}/ v_{Rd}	v_{Ed}/ v_{Rd}	v_{Ed}/ v_{Rd}	v_{Ed}/ v_{Rd}	v_{Ed}/ v_{Rd}
X	S2	0.52	0.32	0.37	0.21	0.30
	S3	0.82	0.25	0.50	0.25	0.29
	S4	0.82	0.25	0.50	0.25	0.29
	S5	0.98	0.28	0.55	0.29	0.32
	S6	0.61	0.35	0.41	0.24	0.34
Y	S2	1.50	0.42	0.56	0.43	0.48
	S3	2.49	0.63	0.56	0.49	0.64
	S4	0.78	0.42	0.49	0.29	0.41
	S5	1.56	0.59	0.50	0.43	0.58
	S6	1.24	0.34	0.65	0.35	0.39

✓

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- Andreas Kappos, CEN TC-250 SC8 MC member

Thank you for Your Attention!