Earthquake Performance Comparison of Multifamily, Multistory Apartment Building Constructed of Various Materials

Prepared by

US Resiliency Council

for

The National Ready Mixed Concrete Association (NRMCA) and the RMC Research & Education Foundation

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Executive Summary

The National Ready Mixed Concrete Association (NRMCA) and the RMC Research & Education Foundation provided the USRC with a grant to conduct a limited study on the comparative seismic performance in Los Angeles, Seattle, and Memphis of a variety of construction types commonly used for multifamily housing, including: traditional wood framing, cross laminated timber (CLT), steel framing and concrete framing using insulated concrete forms (ICF). A common style of a four-story apartment building was used as a template for each of the analyses. Each building was assumed to have been designed to the most current edition of the International Building Code, without any special seismic features beyond code requirements.

NRMCA provided construction costs for each building configuration based on RS Means data. The baseline cost of the ICF configuration ranged from \$15.6 to \$20.5 million depending on location. Construction costs for traditional wood framing ranged from \$14.1 to \$20.0 million depending also on historic variability in lumber prices. For CLT the range was \$15.1 to \$21.7 million and for steel \$16.3 to \$21.5 million.

USRC calculated the net benefits and net construction cost differences of ICF relative to the other three configurations and estimated a potential return on investment considering earthquakes that might occur over a 50 year building life. Benefits included reduced property loss and rental losses associated with the strength and stiffness of each**.** Other potential losses not considered included contents, injuries, shelter needs, workforce losses, tax revenues, debris costs and environmental impacts. USRC estimated the type of USRC Building Earthquake Performance Rating each building configuration might receive.

The key results of the study were:

1. The cost differential among the various material systems considered is relatively minor, typically 6% or less, particularly considering the volatility of lumber and, to a lesser extent, steel.
2. The ICF configuration produced an 18% to 80% higher lateral force strength and four to five times higher building stiffness than the other configurations.
3. Property losses in a Design Level Event were approximately 170% to 270% higher for the wood, CLT and steel configurations than the ICF configuration in Los Angeles and Seattle, and 40% to 85% higher in Memphis.
4. Estimated recovery times in a Design Level Event for the ICF configuration were typically less than two weeks. Recovery times for the other configurations ranged from approximately 6.5 to 9.5 months in Los Angeles and Seattle, and 1.5 to 5.5 months in Memphis.
5. Total losses, considering property and rent were approximately 270% to 530% higher for the wood, CLT and steel configurations than the ICF configuration in Los Angeles and Seattle, and 85% to 130% higher in Memphis.
6. The net benefit in a Design Level Event of the ICF configuration, considering the difference in estimated construction cost, ranged from \$1.0 million to \$5.3 million in Los Angeles and Seattle. In Memphis, the range was between -\$1.5 million (negative benefit) to \$800,000 net benefit.
7. An ICF building might be expected to receive a USRC Gold or Platinum Rating in each location considered. Similar wood and steel framed structures may or may not achieve a USRC Silver Rating based on location.

Scope of Work

The US Resiliency Council (USRC) is a 501(c)3 nonprofit organization with the mission of improving building and community resilience. The National Ready Mixed Concrete Association (NRMCA) and RMC Research & Education Foundation provided the USRC with a grant to conduct a limited study on the comparative performance of a variety of construction types commonly used for multifamily housing, including: traditional wood framing, cross laminated timber (CLT), steel framing and concrete using insulated concrete forms (ICF). The objective of the study was to demonstrate that different structural systems, all permitted within the International Building Code, may nonetheless deliver different performance in earthquakes. While a code compliant building regardless of structural system is expected to provide life safety, the amount of physical damage, repair costs and building functional recovery time can depend significantly on the strength and stiffness of the selected structural system.

The USRC evaluated the seismic performance of the apartment building configuration considering each of four primary construction materials, assuming locations in Los Angeles, Seattle and Memphis. The USRC estimated the repair cost and recovery time associated with damage caused by a range of earthquake intensities at each location.

NRMCA developed and provided building drawings and selected details for a common style of multistory, multifamily apartment building constructed of ICF. The USRC modified the details of construction for traditional wood framed, CLT and steel framed configurations of the building. NRMCA estimated the cost of construction for each building configuration based on the conceptual designs developed by NRMCA and USRC, considering regional cost differences in each location.

USRC calculated the net benefits and net construction costs of ICF relative to the other three configurations and estimated a return on investment over a 50 year building life. Benefits included reduced property loss and rental losses associated with building recovery times**.** USRC estimated the type of USRC Building Earthquake Performance Rating each building configuration might receive.

The USRC relied on NRMCA for estimates of construction costs, which were based on RS Means data, but NRMCA did not provide guidance or review of the engineering analysis and performance estimates for each building configuration.

Building Properties

A common style of four-story apartment building was used as a template for each of the seismic analyses. The building measures 360’ by 68’, approximately 98,000 square feet as shown in Figure 1. The building is clad in stucco, has no basement, and floor heights measure between nine feet and ten and a half feet, depending on the structural system. The building foundation consists of a concrete slab on grade and spread footings interconnected by grade beams.

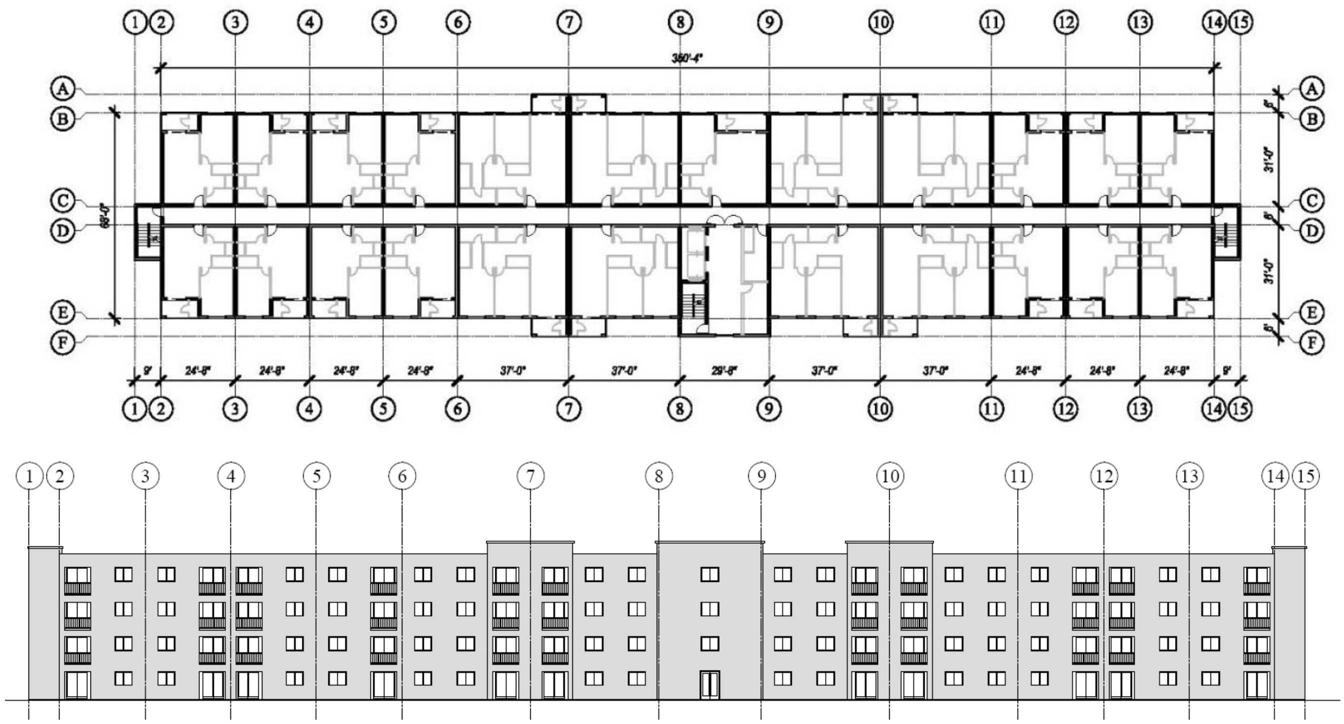


Figure 1 – Apartment building template

Four structural systems were evaluated:

- Insulated Concrete Forms with precast concrete floor slabs
- Traditional stick frame lumber with dimensional lumber floor joists and plywood floor diaphragms
- Traditional stick frame lumber with Cross Laminated Timber floor diaphragms
- Hot rolled steel framing with concrete topped metal deck floor diaphragms.

Specific characteristics of each building material type are listed in Table 1. Typical details of construction are included in the Appendix.

Table 1 – Building construction details

Building Component	Insulated Concrete Forms	Traditional Wood Framing	Cross Laminated Timber	Steel Moment Frame
Floor to floor height	8’-8”	10’-0”	10’-0”	10’-6”
Primary earthquake lateral system	6” and 8” reinforced concrete shear walls (ICF)	Plywood sheathed 2x4 wood stud walls	Plywood sheathed 2x4 wood stud walls	Wide flange steel moment frames
Floor diaphragm construction	8” precast concrete hollow core planks	¾” plywood topped by 1.5” gypcrete, supported on 2x8 and 2x12 dimensional lumber joists spanning to 4x12 wood beams	3-ply cross laminated timber diaphragms topped by 1.5” gypcrete spanning to laminated wood beams an girders	3” metal deck topped with a 3.5” normal weight concrete slab, spanning to wide flange beams and girders
Gravity load bearing elements	6” and 8” reinforced concrete shear walls (ICF)	2x wood stud walls	2x wood stud walls	Steel columns

Building Component	Insulated Concrete Forms	Traditional Wood Framing	Cross Laminated Timber	Steel Moment Frame
Partition walls	Metal stud	2x wood stud	2x wood stud	Metal stud
Ceiling construction	Exposed ceiling except at soffits	1 layer 5/8" gypboard	2 layers 5/8" gypboard	2 layers 5/8" gypboard

Each building configuration was "located" in the three cities at the following addresses:

- 300 N Union Ave, Los Angeles, CA
- 300 Union Street, Seattle, WA
- 300 Union Ave, Memphis, TN

Los Angeles has a very high seismicity, Seattle high seismicity and Memphis moderate seismicity. In the common parlance of the International Building Code, the buildings would be in Seismic Design Category E (Los Angeles) and D (Seattle and Memphis). The purpose of selecting three evaluation cities is to compare the seismic performance of the four building configurations accounting for regional cost of construction, average apartment rental rates, and local seismicity.

Each building was assumed to have been designed to the most current edition of the International Building Code (IBC 2021) based on seismicity defined in the ASCE 7-16 Standard. Each building was evaluated as a non-essential (Risk Category II) building, which would be typical for a residential building. No special seismic features were assumed that would protect the building beyond what the IBC 2021 would require.

Seismic Evaluation Methodology

Each of the twelve building models developed as part of this study (four material configurations and three locations) was subjected to simulated earthquake ground motions representative of the seismicity of each city: Los Angeles, Seattle and Memphis, and associated with different frequencies of occurrence or return periods. Many are familiar with the term "100-year flood," which represents the flood elevation at a specific site that on average occurs once every 100 years, or in another way to describe it, a flood elevation that has a 1% chance of being reached or exceeded in any given year. Similarly with earthquakes, return periods from about 20 years up to approximately 2,500 years were considered in the analysis.

Each building was assumed to have the same overall layout; only the floor heights were unique to the framing system employed as shown in Table 1.

The seismic evaluation software used to perform the analyses is SP3, produced by the company HB-Risk. SP3 models building earthquake performance using a methodology developed over more than fifteen years by FEMA in a standard entitled *P58 - Seismic Performance Assessment of Buildings.* The methodology considers building strength and stiffness properties based on structural material, code design level, location, soil type, height and other factors. It estimates repair costs and recovery time based on the fragility of individual structural and nonstructural components including: walls, floors, frames, cladding, partitions, ceilings, MEP equipment and distribution, and egress systems. FEMA P58 represents the state-of-the-art in seismic performance prediction and is the basis of the US Resiliency Council's Earthquake Building Performance Rating System.

Building Valuations

Construction Costs

Construction costs for each building were estimated based on the size of the building, framing configuration and materials used. NRMCA provided cost estimates based on the most current RS Means data. Cost estimates consider regional pricing in the study cities: Los Angeles, Seattle and Memphis. These cost estimates should be considered at a conceptual level. More accurate estimates would be developed as part of the normal design process.

The variability of lumber pricing has been high over the past several years. Figure 2 shows relative Producer Price Index changes in concrete, lumber and steel pricing since 2009. The price of concrete has been very stable relative to lumber and to a lesser extent, steel. To account for the variability in lumber pricing, an additional evaluation was performed for the Traditional Wood Frame and CLT buildings, assuming lumber pricing at 125% of the current values.

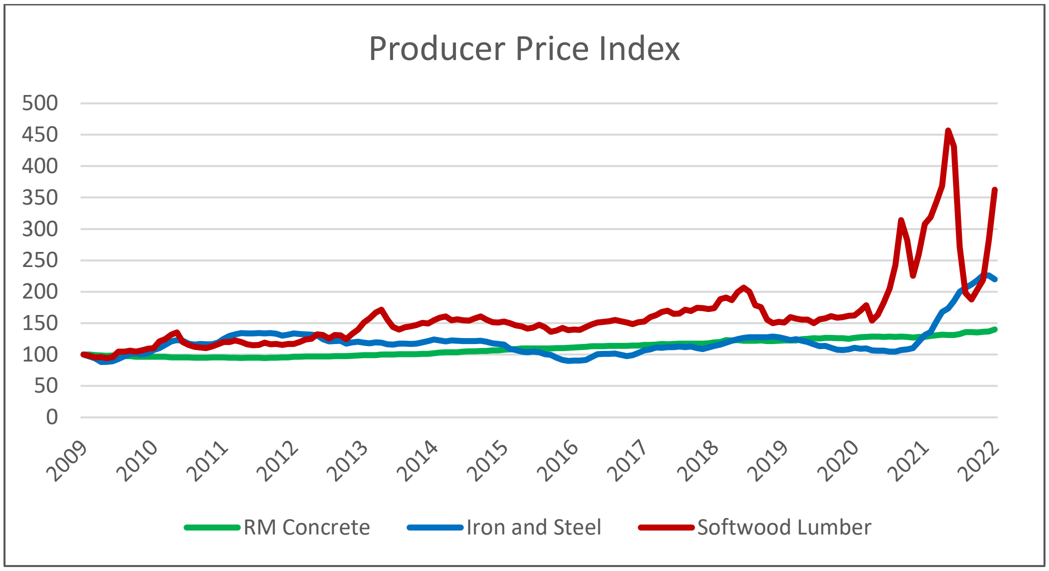


Figure 2 – Producer Price Index building material costs, Source NRMCA

Table 2 shows the estimated construction cost, including overhead and profit for each of the four building configurations, in each of the three cities studied.

Table 2 – Estimated construction costs by material type, February, 2022, Source NRMCA (to nearest $1,000)

	Replacement Cost	Cost differential vs ICF		Cost per square foot
Los Angeles		$	%	
Insulated Concrete Forms	$20,459,000			$209
Wood Frame	$19,323,000	($1,137,000)	(6%)	$197
Wood Frame * 125%	$20,021,000	($439,000)	(2%)	$204
CLT	$20,629,000	$170,000	+1%	$211
CLT * 125%	$21,715,000	$1,256,000	+6%	$222
Steel Frame	$21,523,000	$1,063,000	+5%	$220
Seattle				
Insulated Concrete Forms	$18,880,000			$193
Wood Frame	$17,674,000	($1,206,000)	(6%)	$180
Wood Frame * 125%	$18,286,000	($595,000)	(3%)	$187
CLT	$18,757,000	($123,000)	(1%)	$191
CLT * 125%	$19,699,000	$819,000	+4%	$201
Steel Frame	$20,026,000	$1,146,000	+6%	$204

Memphis				
Insulated Concrete Forms	$15,584,000			$159
Wood Frame	$14,079,000	($1,505,000)	(10%)	$144
Wood Frame * 125%	$14,554,000	($1,031,000)	(7%)	$149
CLT	$15,053,000	($531,000)	(3%)	$154
CLT * 125%	$15,814,000	$229,000	+1%	$161
Steel Frame	$16,319,000	$735,000	+5%	$167

Rental Values

In addition to direct property damage losses, lost rent due to damages resulting in a building being temporarily shut for repairs was also considered. USRC obtained fair market rents (FMR) for a standard one-bedroom and two-bedroom apartment in each of the three cities evaluated. The apartment building considered was assumed to contain 60 one-bedroom units and 32 two-bedroom units. Table 3 below summarizes the monthly rental income per building and calculates the equivalent lost rent per day if the building is not occupiable because of damage and repairs that are needed before functional recovery is regained.

*Table 3 – Fair Market Rents, January 2022**

City	Average FMR / month 1-br	Average FMR / month 2-br	Total FMR / month	Total FMR / day
Los Angeles	$2,913	$3,910	$299,900	$9,997
Seattle	$2,334	$3,652	$256,904	$8,563
Memphis	$1,138	$1,201	$106,712	$3,557

* Source - https://www.apartmentguide.com/blog/apartment-guide-annual-rent-report/#top-100

Other Losses not considered

Beyond direct property losses and loss of rental income, building damage caused by earthquakes will result in additional economic and social impacts. These were not quantified as part of this study but could contribute significantly to the relative benefits of each of the systems considered. They include but are not limited to:

- Contents damage loss
- Injuries sustained from falling debris
- Shelter needs for low income apartment residents who are displaced
- Workforce losses due to displacement
- Loss of city sales tax revenue from lost rent
- Loss of property taxes from depreciated value of damaged buildings
- Costs to haul debris
- Environmental impacts of debris accumulating in landfills

Seismic Evaluation Results

The seismic performance of each of the four building configurations was evaluated for seismic performance in each of the three cities considered. The analysis assumed that each building was built in accordance with IBC 2021 standards for the structural material and location considered. Generally, two characteristics of a building contribute the most to its seismic resilience: ***lateral force strength*** and ***building drift***. Lateral force strength is the equivalent inertial force, generated by the earthquake ground motion that the building is able to withstand. A higher capacity equates to lower expected damages for the same intensity of shaking. Lateral force strength is a function of the building location – buildings in higher seismic areas are required to be designed with a higher capacity in order to not exceed a given damage level – and also the materials used for construction. Some materials have inherently more strength than others, and so when comparing a similar building configuration one building may have a higher overall strength. For example, if the interior corridor walls of the apartment building are constructed of wood stud framing with double sided plywood sheathing over the entire length, or with 6" reinforced concrete ICF walls, the latter will have a higher capacity. This is not a case of "overdesign," but rather just an inherent result of the material used.

Building drift is a measure of the building's stiffness and the amount of deformation it undergoes during an earthquake. Many of a building's components – its structural walls, cladding, partitions, piping and ductwork – are sensitive to the amount of deformation, particularly between one floor and another. Again, certain materials have higher inherent stiffnesses and therefore will produce lower interstory drifts, and generally incur less damage. For example, concrete shear walls are inherently much stiffer than plywood walls or steel frames, so a concrete building will have lower interstory drifts than a comparable wood or steel building.

Figure 3 shows the lateral force strength of each of the four building configurations in each of the three cities considered. Lateral force strength is described as a percentage of gravity, or the percentage of the mass of the building. The value of 68%g for the ICF building in Los Angeles, for example, indicates that the building can resist a lateral force equivalent to 68% of the building's weight. As the figure indicates, the inherent material strength of concrete relative to wood or steel produces a building lateral force strength between 18% to 80% higher depending on location.

Lateral force strength is a description of the ultimate capacity of a building to resist seismic forces. Building Drift, on the other hand is a function of the level of shaking that the building undergoes. Drifts will be less for smaller earthquakes and larger for bigger events. Figure 4 shows the anticipated building drift, in inches, over the height of the building for each of the structural systems, in Los Angeles at the Design Level Event (DLE). The DLE is the intensity of shaking that the code requires buildings be designed to resist. It is commonly measured as a return period or frequency of occurrence. Unlike wind design, however, where a fixed return period of say 100 years might be used in the code, for earthquake the return period varies as a function of the seismicity of the site. For Los Angeles, the DLE equates to a return period of approximately 410 years. As seen in the figure, the ICF is considerably stiffer than either the wood, CLT or steel framed models, undergoing about one quarter to one fifth of the overall deflection at the roof. The floor-to-floor heights of the ICF configuration are approximately 1.5 to two feet shorter than the other configurations. This contributes somewhat to the higher stiffness and lower drifts.

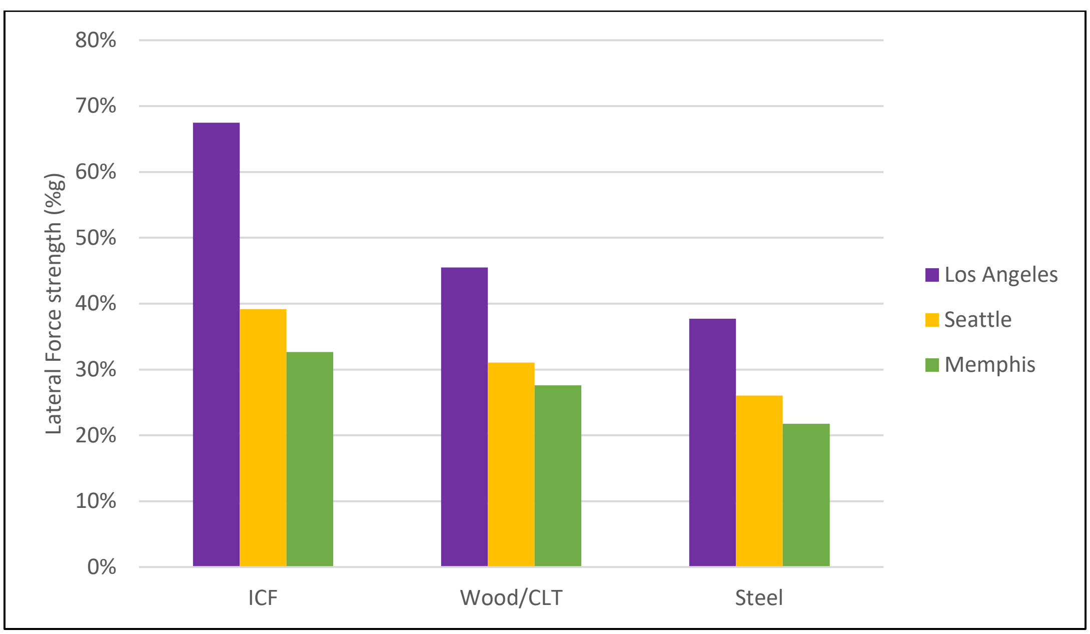


Figure 3 – Building model lateral force capacity

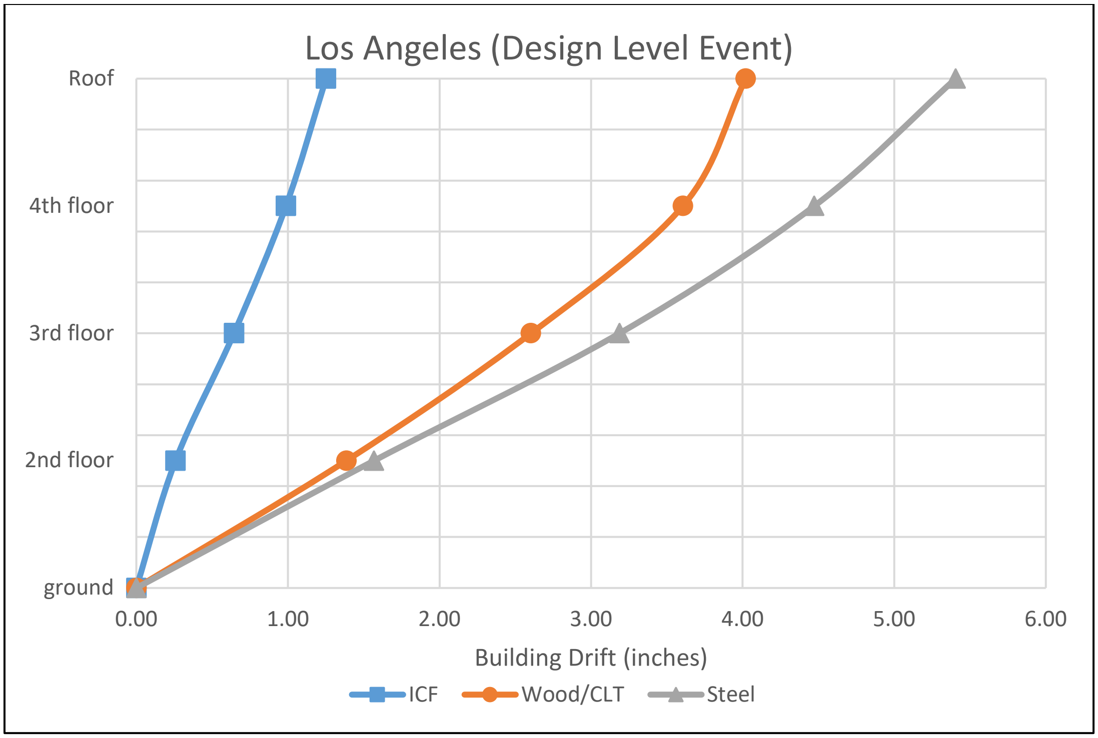


Figure 4 – Building drifts at design level event

Earthquake Loss Estimates

There are typically two indicators of building damage following an earthquake. The first is the amount of time required to regain functional recovery of the building. Functional recovery is a state where the building can be reoccupied and perform its basic functions, even if repairs are ongoing. For the apartment building, this would be the point at which the building can safely house residents and provide them with basic utilities, egress and other code required systems. Nearly all damage to the structure itself would typically have been repaired, as well as damage to utilities, stairs and elevators. If extensive damage to partitions, ceilings and cladding/fenestration has occurred, the bulk of those repairs would likely need to be completed, although touchups and painting might reasonably proceed with the building occupied.

Beyond the time required directly for repairs, construction typically cannot start until an engineer designs the repairs to the building, a building permit is obtained, financing is secured and a builder is under contract. Depending on the severity of the damage to the building and in the surrounding region, these "impeding factors" can add weeks or months to the recovery time.

Figure 5 shows the estimated functional recovery time for each building model in each city, for the DLE. As seen, the recovery time for the ICF building is less than 1-2 weeks, for the wood and CLT buildings it's six to nine months and for the steel building it's about 1.5 to 5.5 months. The dramatic difference can primarily be accounted for by 1) the negligible structural damage in the ICF structure, which would possibly allow for repairs without an engineering design or complicated building permit; and 2) the lower building drifts which would reduce damage to cladding, partitions, and utilities, which can take considerable time to repair.

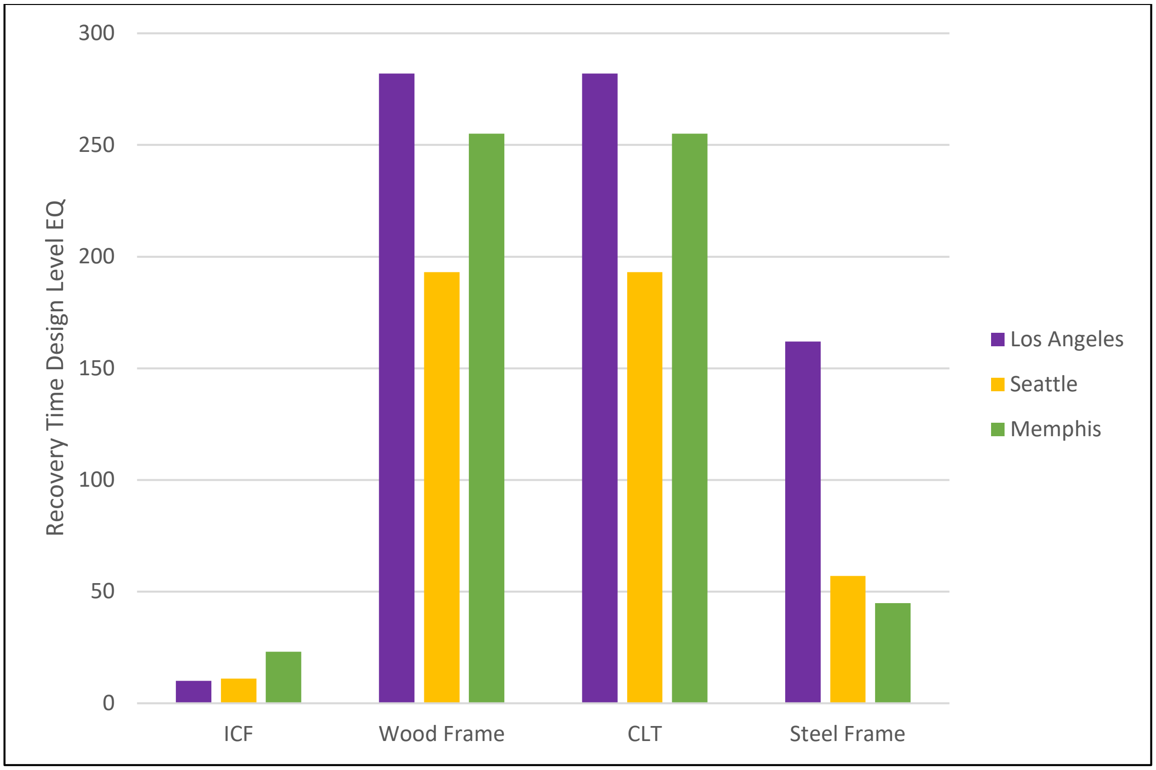


Figure 5 – Functional recovery time (Design Level Earthquake) by building material and location

The second indicator of building damage is the estimated cost of repair. Figure 6 summarizes building losses, both property and rental, for each configuration and location, for the DLE. Property losses are a function of the level of damage and the construction cost of the building. Rental losses are the total rental revenue multiplied by anticipated recovery time. The considerably lower rental losses for the ICF model versus the other materials, is a direct consequence of the lower recovery time shown in Figure 5, and the lower property losses are primarily due to the lower building drifts, an example of which is shown in Figure 4. Table 4 summarizes in tabular form the losses displayed in Figure 6.

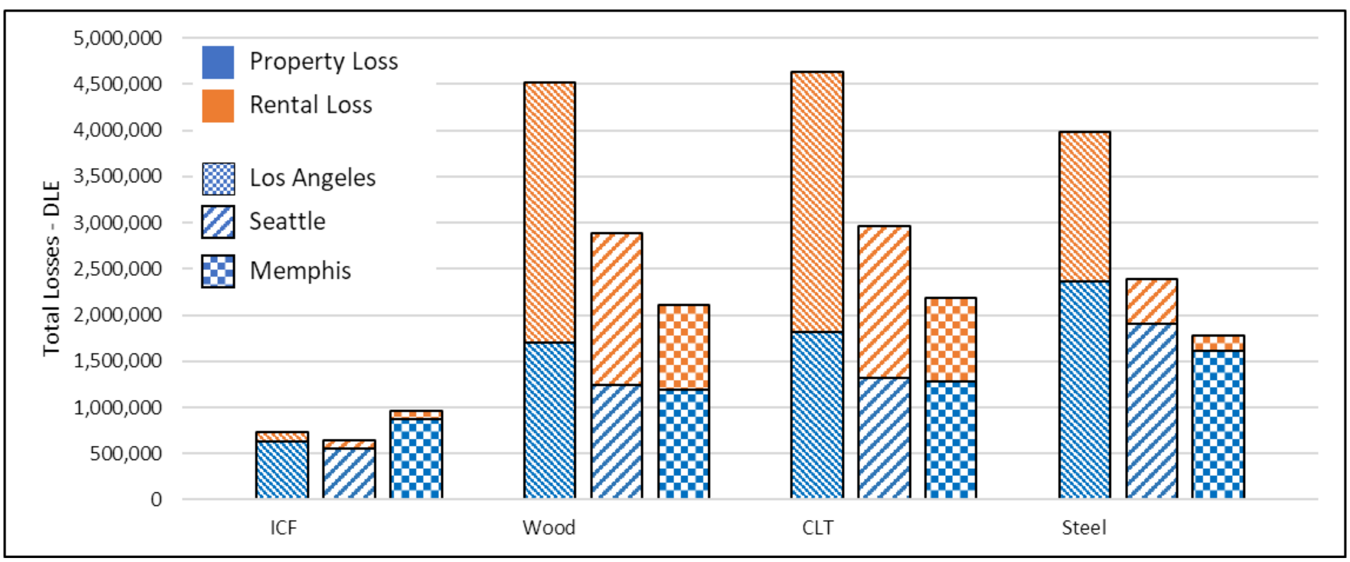


Figure 6 – Property and rental losses (Design Level Earthquake) by building material and location

Table 4 – Summary of building losses (Design Level Event), values in $1,000

	Los Angeles			Seattle			Memphis		
Building Type	**Property Loss**	**Rental Loss**	**Total Loss**	**Property Loss**	**Rental Loss**	**Total Loss**	**Property Loss**	**Rental Loss**	**Total Loss**
ICF	$634	$100	$734	$548	$94	$642	$873	$82	$955
Wood	$1,700	$2,819	$4,519	$1,237	$1,653	$2,890	$1,197	$907	$2,104
CLT	$1,815	$2,819	$4,634	$1,313	$1,653	$2,966	$1,280	$907	$2,187
Steel	$2,368	$1,619	$3,987	$1,903	$488	$2,391	$1,616	$159	$1,775

Return on Investment

From a comparison of the expected performance of each building model and its associated construction cost, a benefit-cost analysis was developed to evaluate the value of selecting one system over another. There are two ways that a benefit-cost analysis can be performed. One is to look at the net benefit – the reduction in loss accounting for the construction cost differential – at a defined level of shaking, such as the Design Level Event. In Table 5, the net benefit of ICF construction over the three other building configurations is summarized for each location, should the building be subject to the DLE. Note that as stated above, not all potential benefits have been included in this analysis. Avoided casualties, shelter costs, debris impacts, and the social and economic impacts to a community due to lost housing and workforce are examples of the additional benefits achieved with higher performing buildings. Therefore, the net benefits shown in Table 5 are a lower bound estimate of the return on investment.

The second way to evaluate benefit and costs is to look at an annual return on investment. The DLE represents an upper bound intensity of shaking that considers the different magnitudes of earthquakes that a building might be subject to over its life. If the losses associated with these earthquakes, and particularly the differences in losses between one model building and another, are annualized over the building lifetime, an annual return on the extra, if any, investment in using the one over the other system can be calculated. In Table 6 below the annual return on investment is summarized, again comparing ICF construction to the other configurations. Cells with a "*" do not have a return on investment because the estimated cost of ICF construction is less than the other material.

Table 5 – Net earthquake benefits – ICF relative to other materials, Design Level Event (to nearest $1,000)

	Gross benefit ICF relative to other systems	Additional cost of ICF relative to other systems	Net Benefit of ICF relative to other systems
Los Angeles			
Wood Frame	$3,785,000	$1,137,000	$2,649,000
Wood Frame * 125%	$3,847,000	$439,000	$3,408,000
CLT	$3,900,000	($170,000)*	$4,070,000
CLT * 125%	$3,996,000	($1,256,000)	$5,252,000
Steel Frame	$3,253,000	($1,063,000)	$4,316,000
Seattle			
Wood Frame	$2,248,000	$1,206,000	$1,042,000
Wood Frame * 125%	$2,291,000	$595,000	$1,696,000
CLT	$2,324,000	$123,000	$2,201,000
CLT * 125%	$2,390,000	($819,000)	$3,209,000
Steel Frame	$1,749,000	($1,146,000)	$2,895,000

Memphis			
Wood Frame	$14,000	$1,505,000	($1,491,000)
Wood Frame * 125%	$22,000	$1,031,000	($1,009,000)
CLT	$30,000	$531,000	($501,000)
CLT * 125%	$42,000	($229,000)	$270,000
Steel Frame	$68,000	($735,000)	$803,000

* Negative values in red represent buildings with construction costs higher than ICF

Table 6 – Return on investment – All materials relative to ICF

Model	Additional initial investment	Annualize reduction in earthquake loses	Return on Investment (50 years)
Los Angeles			
Wood Frame	$1,137,000	$34,440	2%
Wood Frame * 125%	$439,000	$35,363	8%
CLT	†	$36,166	*
CLT * 125%	†	$37,601	*
Steel Frame	†	$34,235	*
Seattle			
Wood Frame	$1,206,000	$18,477	-1%
Wood Frame * 125%	$595,000	$19,076	2%
CLT	$123,000	$19,538	16%
CLT * 125%	†	$20,461	*
Steel Frame	†	$19,907	*
Memphis			
Wood Frame	$1,505,000	$2,116	-8%
Wood Frame * 125%	$1,031,000	$2,203	-7%
CLT	$531,000	$2,294	-5%
CLT * 1.25	†	$2,432	*
Steel Frame	†	$1,113	*

† ICF construction cost is less than other material
* ROI are not applicable when ICF cost less than other material

USRC Earthquake Building Performance Rating

The US Resiliency Council's Earthquake Building Performance Rating System communicates the performance of a building using one to five stars across the three dimensions of Safety, Damage (repair cost), and Recovery Time for an earthquake equivalent to the DLE. Table 7 describes the dimensions and stars levels.

Table 7 – USRC Earthquake Rating Definitions

Rating	SAFETY	DAMAGE	RECOVERY
★★★★★ Platinum	**Injuries and blocking of exit paths unlikely**: Expected performance results in conditions unlikely to cause injuries or to keep people from exiting the building.	**Minimal damage**: Repair Cost likely less than 5% of building replacement cost.	**Within hours to days**: Expected performance will likely result in people being able to quickly re-enter and resume use of the building from immediately to a few days.
★★★★ Gold	**Serious injuries unlikely**: Expected performance results in conditions that are unlikely to cause serious injuries.	**Moderate damage**: Repair Cost likely less than 10% of building replacement cost.	**Within days to weeks**: The expected performance may result in delay of minimum operational use for days to weeks.
★★★ Silver	**Loss of life unlikely**: Expected performance results in conditions that are unlikely to cause loss of life.	**Significant damage**: Repair Cost likely less than 20% of building replacement cost.	**Within weeks to months**: The expected performance may result in delay of minimum operational use for weeks to months.
★★	**Loss of life possible in isolated locations**: Expected performance results in conditions associated with partial collapse or falling objects.	**Substantial damage**: Repair Cost likely less than 40% of building replacement cost.	**Within months to a year**: Expected performance may result in delay of minimum operational use for months to a year.
★	**Loss of life likely in the building**: Expected performance results in conditions associated with building collapse.	**Severe damage**: Repair Cost likely greater than 40% of building replacement cost.	**More than one year**: Expected performance may result in delay of minimum operational use for at one year or more.

A modern code compliant building might expect to receive three to four stars in Safety, and two to three stars in Damage and Recovery. This represents a building that will be safe for its occupants, as the code intends, but not one that is necessarily repairable quickly. A USRC Gold or Platinum Rating (four and five stars in all three dimensions) would ordinarily be limited to essential or critical facilities, perhaps five to ten percent of the building stock. A well-designed ordinary building might be expected to achieve a Silver Rating (a minimum of three stars in each dimension).

Table 8 shows the likely USRC Ratings each of the modeled buildings might receive. The wood frame, CLT and steel frame buildings perform about as expected for standard, non-essential residential facilities, perhaps slightly better in the Damage dimension. The ICF building performs noticeably better in all three dimensions and would likely receive a Gold to Platinum Rating primarily because of the material's inherent strength and stiffness and the relative simplicity of residential MEP and other systems. A Gold to Platinum rating implies that the building will be safe to egress following a DLE and will be able to return to basic functionality within one to two weeks.

Table 8 – USRC Ratings for modeled buildings

Model	USRC SAFETY Rating	USRC DAMAGE Rating	USRC RECOVERY Rating	Overall USRC Rating
Los Angeles				
ICF	★★★★★	★★★★★	★★★★(★)	**Gold to Platinum**
Wood Frame	★★★★	★★★★	★★	
CLT	★★★★	★★★★	★★	
Steel Frame	★★★★	★★★	★★★	**Silver**
Seattle				
ICF	★★★★★	★★★★★	★★★★(★)	**Gold to Platinum**
Wood Frame	★★★★	★★★★	★★★	**Silver**
CLT	★★★★	★★★★	★★★	**Silver**
Steel Frame	★★★★	★★★★	★★★	**Silver**
Memphis				
ICF	★★★★★	★★★★★	★★★★(★)	**Gold to Platinum**
Wood Frame	★★★★	★★★★	★★	
CLT	★★★★	★★★★	★★	
Steel Frame	★★★★	★★★	★★★	**Silver**

Conclusions

Several conclusions can be drawn from the results of this study:

1. The cost differential among the various material systems considered is relatively minor, typically 6% or less, particularly considering the variability of lumber and, to a lesser extent, steel.
2. While the design of each building option was targeted to basic conformance to the International Building Code, the performance of ICF showed both higher strength and higher building stiffness compared to the traditional wood frame, CLT and steel frame configurations.
3. In a Code Design Level Event, the ICF configurations showed significantly less building drift than the other configurations, with roof deflections of the former on the order of 20-25% of the latter.
4. Property losses in a Design Level Event were approximately 170% to 270% higher for the wood, CLT and steel configurations than the ICF configuration in Los Angeles and Seattle, and from 40% to 85% higher in Memphis.
5. The additional strength and stiffness of the ICF configurations resulted in substantially reduced recovery time relative to the other configurations, primarily because minimal structural damage is caused, and nonstructural damage to partitions, cladding, utilities and egress routes is likely to be significantly less as a result of the lower building drifts. Estimated recovery times in a Design Level Event for the ICF configuration were typically less than two weeks. Recovery times for the other configurations ranged from approximately 6.5 to 9.5 months in Los Angeles and Seattle, and 1.5 to 5.5 months in Memphis.
6. Total losses, considering property and rent, were approximately 270% to 530% higher for the wood, CLT and steel configurations than the ICF configuration in Los Angeles and Seattle, and 85% to 130% higher in Memphis.

7. The net benefit in terms of the reduced losses considered in a Design Level Event, which included direct property damage and lost rental revenue, accounting for the difference in estimated construction cost of ICF construction relative to other materials, ranges from $2.6 million to $5.3 million in Los Angeles and from $1.0 million to $3.2 million in Seattle. In Memphis, where the seismicity is substantially lower than on the west coast, the net benefits are less, between -$1.5 million net cost of the ICF system relative to wood, and $800 thousand net benefit relative to steel.
8. Considering the annual benefit of reduced losses over time relative to additional construction costs, in Los Angeles the 50-year ROI ranges from 2% to 8% and in Seattle from -1% to 16%. In Memphis, the return on investment was generally negative from -8% to -5%.
9. Not all potential benefits have been included in this analysis. Avoided casualties, shelter costs, debris impacts, and the social and economic impacts to a community due to lost housing and workforce are examples of the additional benefits achieved with higher performing buildings. Therefore, the net benefits associated with ICF construction are a lower bound estimate of the return on investment.
10. An ICF building might be expected to receive a USRC Gold or Platinum Rating where egress from the building is not hindered following a Design Level Event, repair costs would be less than 5% of the building replacement cost, and functional recovery could be restored within one to two weeks.
11. Similar wood and steel framed structures may or may not achieve a USRC Silver Rating, implying that because of larger building drifts occupants may be hindered in using stairs or elevators to exit, and functional recovery time might be on the order of several months to a year.

Limitations

Proper application of this study requires recognition and understanding of the limitations of both the scope and methodology of the entire study. The building earthquake performance estimates are based on mathematical and statistical modeling of physical properties of the building configurations considered, as well as site-specific ground shaking resulting from specific earthquake events. Building evaluations were based on conceptual, not detailed building designs. Given the nature of these evaluations, which in some cases may be based on limited information, uncertainties are associated with both the initial assumptions, including RS Means cost information provided by NRMCA, and the study results.

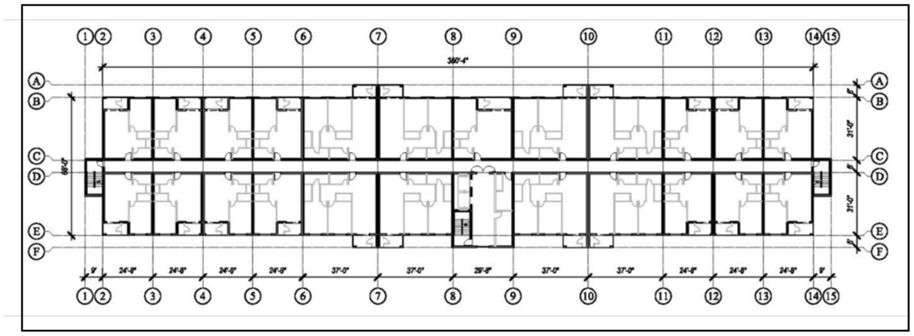
Therefore, while results may be presented in precise terms, precision does not imply accuracy beyond the limitations and uncertainties inherent in the assumptions and analysis methodologies. Results should not be considered a guarantee of relative performance between the building configurations considered.

Acknowledgement

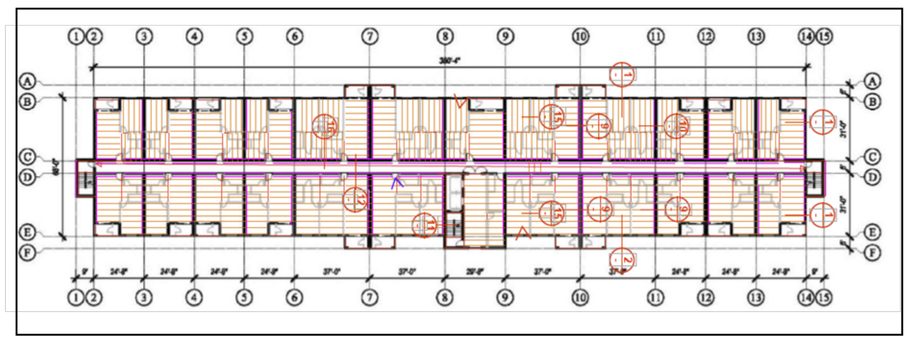
The US Resiliency Council is grateful to the National Ready Mixed Concrete Association and the RMC Research & Education Foundation for their funding of this project.

Appendix – Building Construction Details

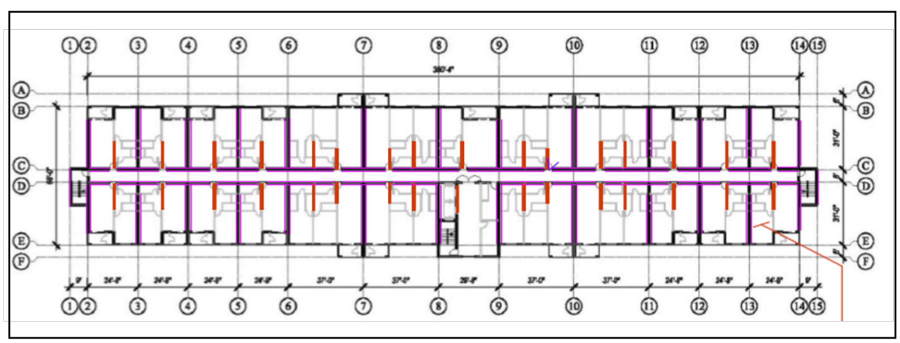
(a)



(b)



(c)



(d)

Figure A - 1: Typical floor plans (a) ICF, (b) traditional wood, (c) CLT, (d) steel frame

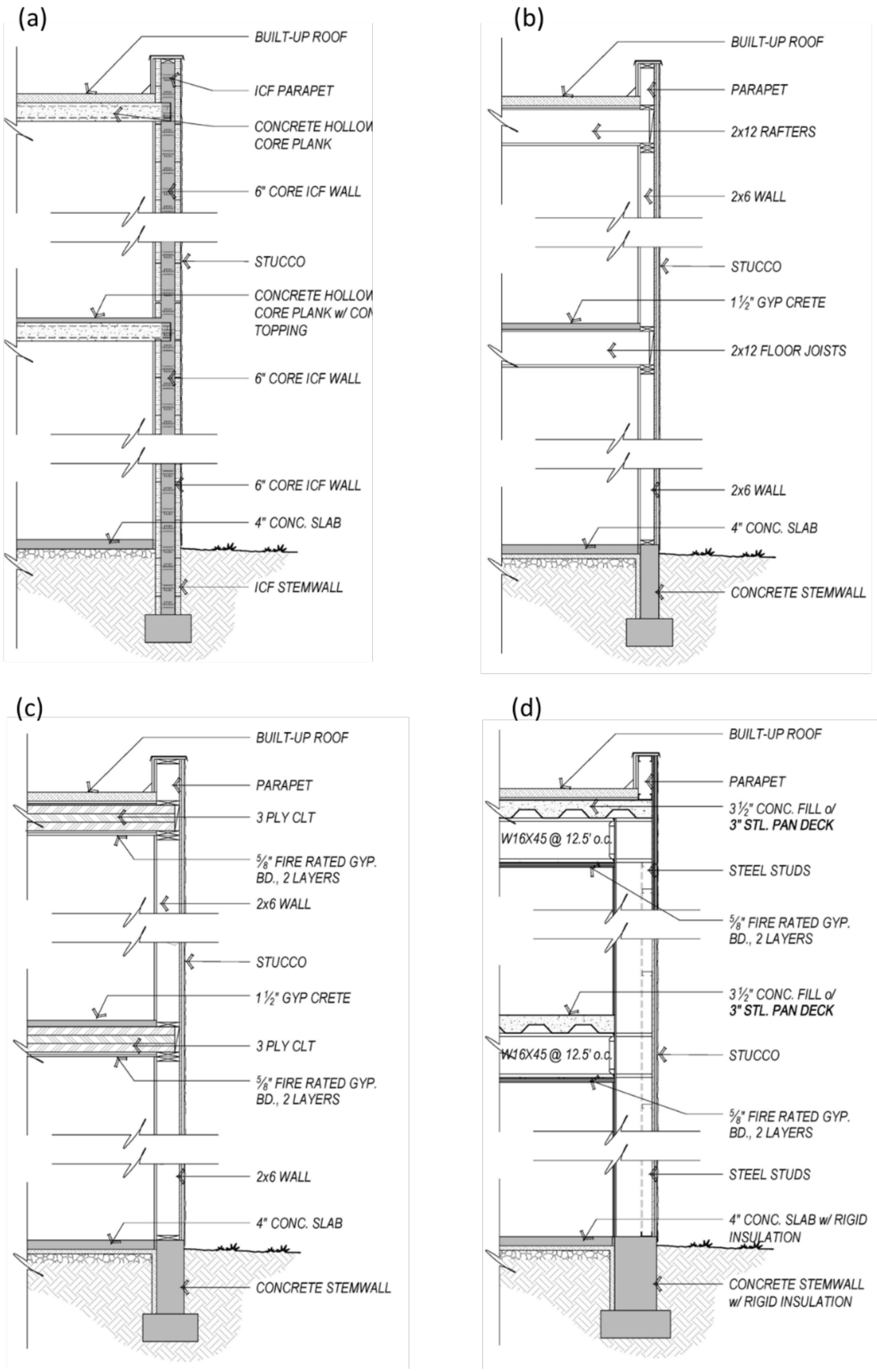


Figure A - 2: Typical exterior wall sections (a) ICF, (b) traditional wood, (c) CLT, (d) steel frame

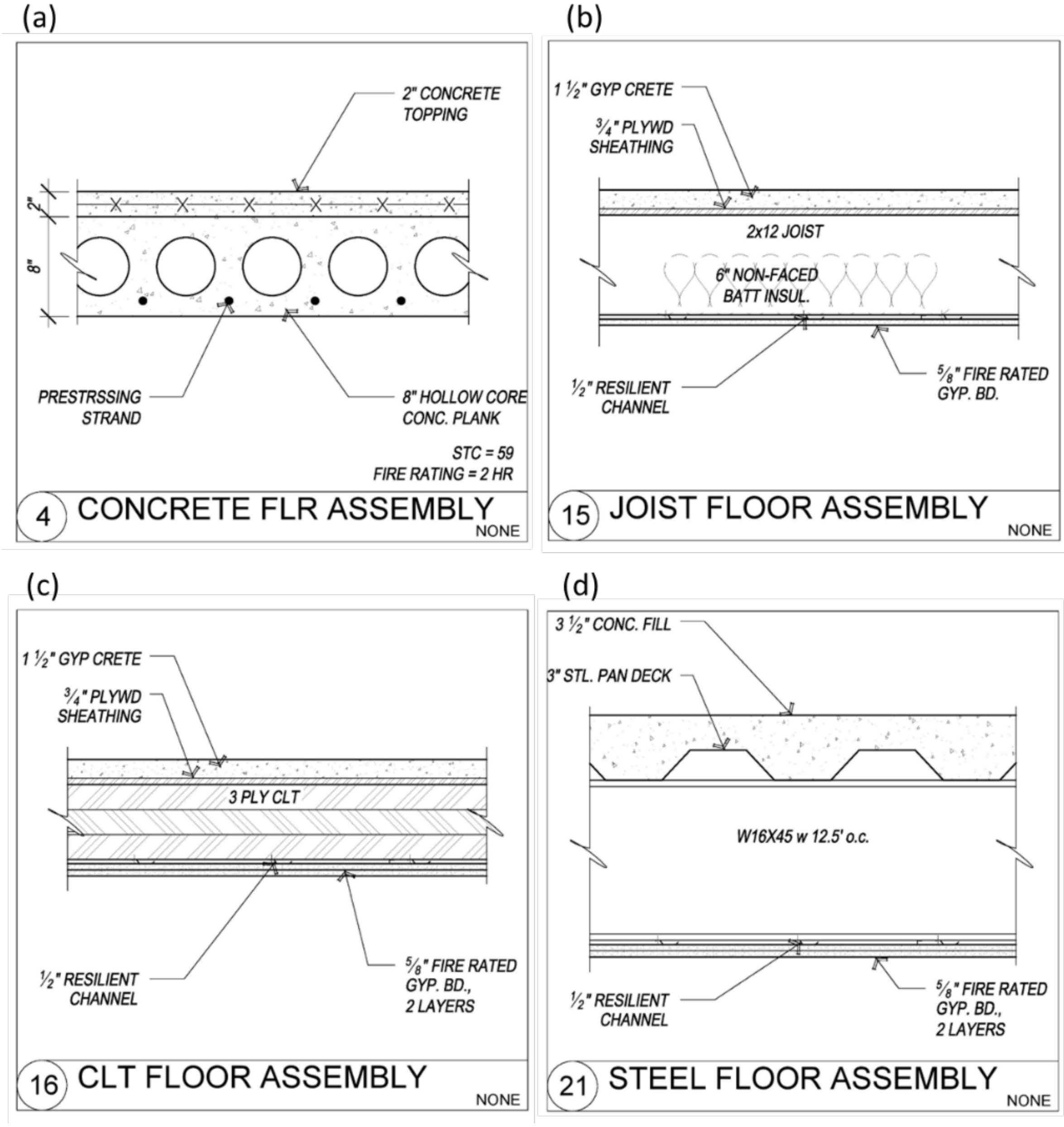


Figure A - 3: Typical floor assemblies (a) ICF, (b) traditional wood, (c) CLT, (d) steel frame