

## Appendix A

### ANALYSIS OF THE MODEL HOUSE USED IN THIS GUIDE

A model single-family detached house was developed and analyzed in preparing this guide. The house is described in Chapter 1, and the results of the analysis are referred to throughout the guide. This appendix provides additional details concerning the model house, the analysis, and the interpretation of analysis results.

The analysis of the model house provided an approximate comparison of performance for varying wood light-frame house and bracing configurations permitted by the *IRC* and permitted the assessment of improved performance resulting from application of the **above-code** recommendations made in this guide. While the model house and the analysis performed cannot represent all houses that may be constructed using *IRC* provisions, they do provide a specific example of relative performance from which trends can be observed.

#### A1 MODEL HOUSE

The model house contained both one-story and two-story portions, three bedrooms, 2-1/2 baths, and an area of approximately 2,500 square feet plus garage. The house design is intended to reflect current configurations for wood light-frame construction but not necessarily any specific region of the United States. Separate analytical models were developed for common variations in the design including base conditions, exterior finishes, and earthquake bracing configurations.

The base conditions are slab-on-grade construction with turned-down footings (Figure A-1), continuous exterior footings with level 2-foot-high cripple walls (Figure A-2), a hillside condition with cripple walls of varying height (Figure A-3), and a full basement with concrete or masonry walls (Figure A-4). Exterior finishes are categorized as light and veneer. The light finish is intended to represent low-weight finishes such as vinyl or fiber-cement board siding. The veneer is intended to represent a single-wythe anchored brick veneer used for the entire house exterior. Bracing requirements were determined for each configuration and Seismic Design Category (SDC) in accordance with the 2003 *IRC*. Chimneys of light-frame construction were used for all house configurations.



Figure A-1 Slab on grade base.



Figure A-2 Level cripple wall base.

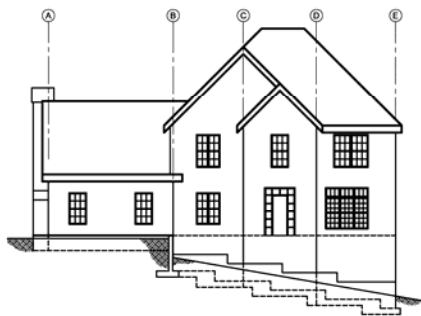


Figure A-3 Hillside base.

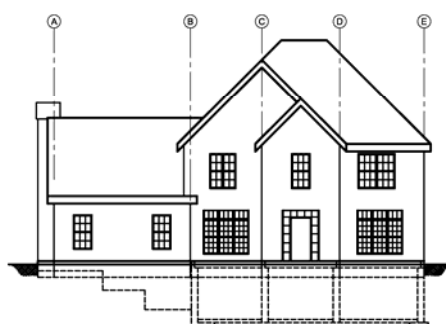


Figure A-4 Basement.

*IRC* prescriptive bracing requirements were determined for each combination of base condition, exterior finish, and Seismic Design Category. Because use of veneer is not permitted on houses with cripple walls in SDC D<sub>1</sub> and D<sub>2</sub> (*IRC* Section R703.7, Exceptions 3 and 4), both the level and hillside cripple wall configurations with veneer were limited to SDC C. Table A-1 is an example of one bracing spreadsheet. The remaining spreadsheets used in determining bracing requirements for each of the designs are not included here due to their length; however, they and other information used in the analysis are available upon request from the Building Seismic Safety Council.

Because gypsum wallboard is used in almost every U.S. residential building, it was used for the structural bracing wherever possible. Since it would be installed as a finish anyway, its use for bracing has the least construction cost. Wood structural panel wall bracing was used where length and percentage bracing requirements could not be met with gypsum wallboard. Alternative braced wall panels conforming to *IRC* Section R602.10.6 were used for the slender walls at the house front and garage front for slab-on-grade and basement base conditions. The alternative braced wall panels require support directly on a continuous foundation; therefore, they could not be used in combination with cripple walls. The *IRC* Section R602.10.5

“continuous structural panel sheathing” modifications to bracing length and percent were not used. See Figure 5-6a through 5-6b for an example bracing plan of a cripple wall base condition in SDC C.

Several interpretations of *IRC* requirements were made in developing the bracing designs. First, it was recognized that the roof-plus-ceiling assembly weight would fall just below the limit of 15 psf of *IRC* Section R301.2.2.2.1 if the roof assembly weight were considered based on the unit weight on slope (12:12 roof slope) but would exceed 15 psf if the weight were adjusted to horizontal projected area. Although adjustment to the horizontal projected area is common practice in engineering calculations, it was decided that this calculation is not specifically noted in the 2003 *IRC* provisions so the roof-plus-ceiling assembly weight was deemed to fall within the 15 psf *IRC* limit.

The second interpretation related to the use of gypsum wallboard bracing (*IRC* Section R602.10.3, Method 5). *IRC* Section R602.10.4 requires that gypsum wallboard braced wall panels applied to one side of a wall be at least 8 feet in width. It was interpreted to mean that a continuous length of full-height wall not less than 8 feet wide would have to be available in order to use this bracing method. Interruption of the 8-foot length by perpendicular walls was interpreted to mean that it was not permitted. Where an 8-foot length of full-height wall was not available, wood structural panels were used as bracing instead. Based on this interpretation and the configuration of the model house, wood structural panels rather than gypsum wallboard were used for a significant portion of the exterior wall bracing. Where gypsum wallboard bracing can be applied to both faces of a wall (such as at interior walls), the minimum required length of full-height sheathing is reduced to 4 feet. While the perforated shear wall method that includes hold-down anchorage at the ends of the wall line was used as an **above-code** option for the analysis, the continuous sheathed option of *IRC* Section R602.10.5 that allows a 10 percent reduction in the sheathing percentage was not used in the analysis.

The third interpretation relates to the bracing requirements used for the model house in SDC C. *IRC* Table R602.10.1 specifically identifies sheathing length requirements for SDC C. Some *IRC* users, however, interpret the *IRC* Section R301.2.2 exception to mean that the table bracing length requirements for SDCs A and B can be used for houses in SDC C. Analysis of the model house performed for this guide used the SDC C bracing length requirements.

The resulting bracing configurations are illustrated on a set of bracing plans and elevations for each of the designs are available from the Building Seismic Safety Council on a CD-ROM. The increased bracing length requirements for higher Seismic Design Categories can be observed to have reduced allowable door and window openings.

**Table A-1 Example Wall Bracing per 2003 IRC, Slab-on-grade Base Condition**

Seismic Design Category	Wall Finish	Total Stories	Story Considered	Wall Line	Wall Line Length (ft)	Type 3 Percent	Type 3 Length (ft)	Other Type Percent	Other Type Length (ft)	Adjustments				Type 3 Adjusted Length (ft)	Other Type Adjusted Length (ft)	
										Wall Line Spacing R602.10.1.1	Wall Wt. Table R602.10.3 Footnote d (1)	Roof + Ceil. Table R301.2.2.4	Veneer R703.7 Exc. 2			
C	light	2	2	B	33.5	16	5.4	25	8.4	1.06	0.85	1.00	1.00	4.8	7.5	
			2	E	30	16	4.8	25	7.5	1.06	1.00	1.00	1.00	5.1	7.9	
			2	1,7	37	16	5.9	25	9.3	9.3	1.00	1.00	1.00	1.00	5.9	9.3
			2	5,6	37	16	5.9	25	9.3	9.3	1.00	1.00	1.00	1.00	5.9	9.3
		1 (2)	1	A	40	16	6.4	25	10.0	10.0	1.00	1.00	1.00	1.00	6.4	10.0
			1	1	20	16	3.2	25	5.0	5.0	1.14	1.00	1.00	1.00	3.7	5.7
			1	8	20	16	3.2	25	5.0	5.0	1.14	1.00	1.00	1.00	3.7	5.7
			1	B	40	30	12.0	45	18.0	18.0	1.06	0.85	1.00	1.00	10.8	16.2
		2	1	E	29	30	8.7	45	13.1	13.1	1.06	0.85	1.00	1.00	7.8	11.7
			1	2	37	30	11.1	45	16.7	16.7	1.00	0.85	1.00	1.00	9.4	14.2
			1	5,6	37	30	11.1	45	16.7	16.7	1.00	0.85	1.00	1.00	9.4	14.2
			1	5,6	37	30	11.1	45	16.7	16.7	1.00	0.85	1.00	1.00	9.4	14.2
C	veneer	2	2	B	33.5	16	5.4	25	8.4	1.06	1.00	1.00	1.00	5.7	8.9	
			2	E	30	16	4.8	25	7.5	7.5	1.06	1.00	1.00	1.00	5.1	7.9
			2	1,7	37	16	5.9	25	9.3	9.3	1.00	1.00	1.00	1.00	5.9	9.3
			2	5,6	37	16	5.9	25	9.3	9.3	1.00	1.00	1.00	1.00	5.9	9.3
		1 (2)	1	A	40	16	6.4	25	10.0	10.0	1.00	1.00	1.00	1.00	6.4	10.0
			1	1	20	16	3.2	25	5.0	5.0	1.14	1.00	1.00	1.00	3.7	5.7
			1	8	20	16	3.2	25	5.0	5.0	1.14	1.00	1.00	1.00	3.7	5.7
			1	B	40	30	12.0	45	18.0	18.0	1.06	1.00	1.00	1.50	19.0	28.5
		2	1	E	29	30	8.7	45	13.1	13.1	1.06	1.00	1.00	1.50	13.8	20.7
			1	2	37	30	11.1	45	16.7	16.7	1.00	1.00	1.00	1.50	16.7	25.0
			1	5,6,7	37	30	11.1	45	16.7	16.7	1.00	1.00	1.00	1.50	16.7	25.0
			1	5,6,7	37	30	11.1	45	16.7	16.7	1.00	1.00	1.00	1.50	16.7	25.0

<sup>1</sup>Reduction cannot be applied to top-most story where resulting bracing length would be less than required for wind.

<sup>2</sup>The garage and family room areas are treated as a one-story building attached to the two-story house.

## **A2 ANALYSIS USING STANDARD ENGINEERED DESIGN METHODS**

Prior to evaluation using other methods, earthquake forces and deformations were estimated using the linear static methods commonly used in engineering design of new buildings. Included were force calculations using the *International Building Code (IBC)* linear static method, estimation of drift using the APA-The Engineered Wood Association four-term shear wall deflection equations at strength level forces, and amplification to estimated drifts using *IBC* amplification factors. This approach resulted in the APA shear wall deflection equations being used outside of their intended range (based on force per nail limits included with nail slip variables). This provided clearly unrealistic shear wall deflections amplified to unrealistic estimated drifts (over 36 inch drifts in some cases). Thus, it was concluded that the use of these engineered design estimates as predictors of performance for non-engineered buildings was not realistic and it was not pursued. Likewise, use of other available deflection equations that represent simplifications of the APA equations were not pursued. This issue should not occur when using this standard deflection calculation method for engineered buildings.

## **A3 ANALYSIS USING NONLINEAR METHODS**

Nonlinear time-history analysis using the Seismic Analysis of Woodframe Structures (SAWS) analysis program was chosen as the best available method for estimating force and deformation demands based on analytical studies that were verified against shake table results from the FEMA-funded CUREE-Caltech Woodframe Project. Analysis models included both designated bracing and finish materials. The Woodframe Project analytically predicted forces and deflections compared favorably with shake-table results and were clearly differentiated from analysis and testing results without finish materials (Folz and Filiatrault, 2002).

The SAWS analysis program uses rigid diaphragms to represent floor and roof diaphragms. Walls are modeled as nonlinear springs with hysteretic parameters developed specifically to describe the behavior of woodframe bracing systems. For the example house, rigid diaphragms were used to represent the high roof, the low roof plus second floor, and, where appropriate, the first floor. A simplified representation of the rigid diaphragms and wall springs for the model house is presented in Figure A-5.

Ten sets of hysteretic parameters were developed from component testing data to describe wall bracing and interior gypsum wallboard finishes. Figure A-6 illustrates the meaning of the parameters, and a summary of analytical modeling parameter values is provided in Table A-2. For each of the bracing materials (with the exception of No. 5 and 6), the hysteretic parameters were determined for a 4-foot bracing length. Because widely varying lengths are used in the house, the parameters were scaled for varying bracing lengths.

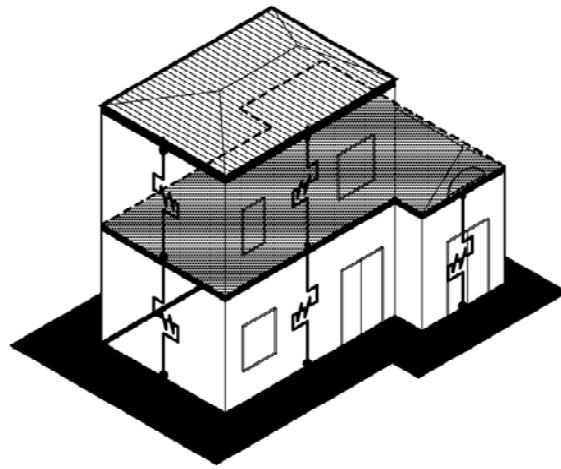


Figure A-5 Analysis model.

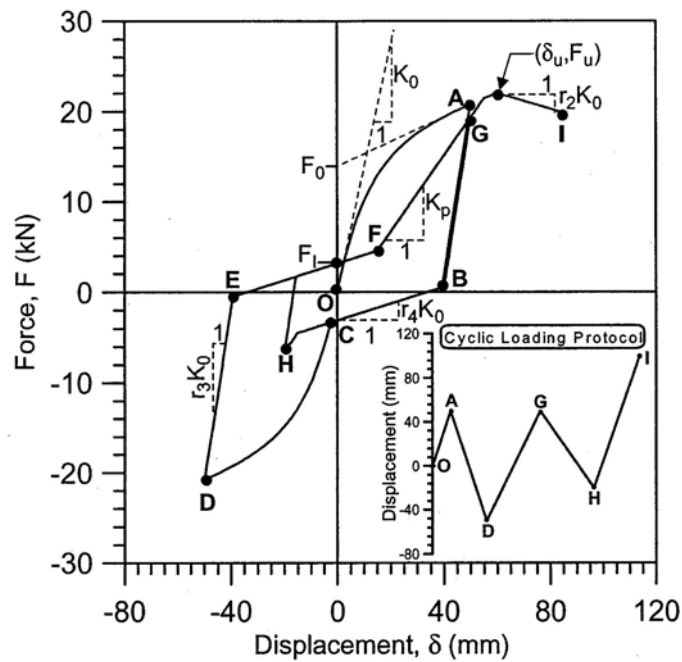


Figure A-6 Hysteretic parameters for model ((Folz and Filiatrault, 2002).

Hysteretic parameters currently available from laboratory testing of wall components vary based on wall boundary conditions, test set-up, and test protocol. Parameters chosen for the analysis of

the model house tended towards lower bounds of strength and stiffness. Future analytical studies should consider exploring upper and lower bounds.

In order to simplify interpretation of analysis results, the analysis model uses consistent identification of bracing walls across all building configurations. Because of this modeling approach, cripple walls have been included in the model for all building configurations; where slab-on-grade construction occurs, the cripple walls are modeled as extremely rigid elements (Property No. 9) resulting in negligible deflection. In addition, some wall elements occur only in limited configurations; a bracing length of 0.1 foot is used where a bracing panel is intended to have no effect.

**Table A-2 Hysteretic Parameters Used for Nonlinear Dynamic Model**

Property No.	Use	Fo (k)	Fi (k)	Δ <sub>u</sub> (in)	So (Ko) (k/in)	r1	r2	r3	r4	alpha	beta	Δ <sub>CUREE</sub> (in)	Fu
<b>Basic Model Properties</b>													
3	gypsum wallboard lower bound <sup>1</sup>	0.50	0.20	0.70	3.0	0.130	-0.050	1.000	0.030	0.40	1.10	0.80	0.47
4	4 ft OSB w/o tie-down	0.59	0.15	1.00	2.8	0.096	-0.021	1.000	0.010	0.40	1.10	1.90	0.63
5	2'-8" wall one-sided	1.20	0.20	2.70	3.0	0.020	-0.100	1.000	0.024	0.87	1.10	2.00	0.62
6	2'-8" wall two-sided	2.40	0.40	2.70	6.0	0.020	-0.100	1.000	0.024	0.87	1.10	2.00	1.24
7	2 ft high cripple wall <sup>1</sup>	3.00	0.30	1.00	20.0	0.010	-0.050	1.000	0.010	0.87	1.10	1.00	3.20
8	1:3 stepped cripple wall <sup>1</sup>	3.30	0.60	1.00	23.0	0.090	-0.110	1.000	0.040	0.87	1.10	0.90	5.48
9	zero height cripple wall = 100 x No. 7	300.00	30.00	1.00	2000.0	0.010	-0.050	1.000	0.010	0.87	1.10	1.00	320.00
<b>Code Plus Properties</b>													
10	Code Plus fully sheathed perforated shear wall <sup>1</sup>	2.30	0.05	2.20	2.6	0.200	-1.000	1.000	0.020	0.87	1.10	1.50	3.00
11	4 ft OSB w/ tie-down	1.70	0.50	3.00	6.8	0.040	-0.056	1.000	0.024	0.87	1.10	2.60	2.51
12													

<sup>1</sup>Values in table are for 4 ft length. Fo, Fi & Ko in model are scaled by length of full height sheathing. See separate spreadsheets.

The strength and stiffness contribution of exterior wall finishes was not included in the analysis. This approach was chosen because it would lead to a lower bound and, therefore, conservative estimate of deformation demand. In addition, some exterior finish materials are believed to have very little impact on building behavior (e.g., vinyl siding) and information was not available on the contribution of some other finishes (e.g., brick veneer). Due to the judgment necessary to select appropriate component testing and to derive parameters and the simplification of not including exterior finishes, the resulting modeling must be qualified as being approximate.

Earthquake demand is represented using the larger horizontal acceleration record from Canoga Park for the 1994 Northridge, California, earthquake. This record was chosen because it corresponds well with the code design spectra over a range of building periods. The peak acceleration was scaled for each Seismic Design Category by dividing the maximum  $S_{DS}$  value for each category by 2.5, resulting in peak accelerations of 0.2, 0.33 and 0.47g for SDCs C, D<sub>1</sub>, and D<sub>2</sub>, respectively. For comparison, the recorded ground motion has a peak acceleration of

0.42g and was scaled to 0.50g to represent Zone 4 anticipated ground motions in the CUREE shake-table testing. The ground motion scaling used for this analysis represents the demand used as a basis for code design. The demand from the maximum considered earthquake (MCE) ground motion (MCE) would be approximately 50 percent greater.

Detailed assembly weights and building weights have been determined for each house configuration. The analysis model spreads the resulting mass uniformly over a single rectangle used to describe each above-ground diaphragm. The center of the mass rectangle is set at the calculated center of mass of the building. This simplification, made necessary by analysis limitations, should have a minor effect on results.

## A4 ANALYSIS RESULTS

The selected ground motion was run once in the horizontal X-direction and once in the horizontal Y-direction for each combination of base condition, exterior finish, and Seismic Design Category as well as for a series of **above-code** recommendations. From the nonlinear time-history analysis, peak drifts in each of the bracing wall lines and peak reactions to supporting foundations were extracted and summarized in tables. These tables are not included here for brevity but are available upon request from the Building Seismic Safety Council on the analysis CD. The “controlling” value was the largest absolute value of the X- and Y-directions.

### A4.1 Deformation Demand Relation to Performance

In order to translate the results of the analysis into an approximation of house performance, three ranges of peak transient wall drift and associated approximate descriptions of building performance were developed. The choice of range and description of performance are based on component and full-building test results combined with the opinions of those participating in the development of this guide.

The approximate performance categories and corresponding drift ranges are:

- **Minor** damage potential – Less than or equal to 0.5% story drift

The house is assumed to suffer minor nonstructural damage such as cracked plaster or gypsum wallboard and hopefully would be “green-tagged” (occupancy not limited) by inspectors after an earthquake, which would permit immediate occupancy. Some repairs should still be anticipated.

- **Moderate** damage potential – Above 0.5% to 1.5% story drift

The house is assumed to suffer moderate damage including possible significant damage to materials and associated structural damage, but the building is assumed to have some reserve capacity in terms of strength and displacement capacity. The house hopefully would be “green-tagged” or,

more likely, “yellow-tagged” (limited occupancy) by inspectors after an earthquake and may or may not be habitable. Significant repairs should be anticipated.

- **Significant** damage potential – Greater than 1.5% story drift

The house is assumed to have significant structural and nonstructural damage that could result in its being “red-tagged” (occupancy prohibited) by inspectors after an earthquake. Significant repairs to most components of the building should be anticipated, and it may be more economical to replace the house rather than repair it.

Use of these three categories permits an approximate comparison of the relative performance of different *IRC* bracing solutions and **above-code** recommendations.

#### A4.2 Discussion of Results

Selected results of peak drift values and approximate performance category are provided in Tables A-3 and A-4. In most cases, the drift increased with increased SDC in spite of the bracing requirements also having increased. The approximate performance often increased from minor or moderate to significant as the SDC went from C to D<sub>2</sub>. The primary reason is the inclusion of interior gypsum wallboard in the models for all Seismic Design Categories. As the SDC increased, interior walls became required braced wall panels per *IRC* requirements rather than simply nonstructural partition walls; however, the analytical model did not change because the interior walls had already been included. The result was application of a higher demand to a model with only nominal increases in resistance.

**Table A-3 Selected Results for *IRC* Bracing Provisions, Slab-on-grade Base Condition**

Walls	Seismic Design Category	1st Story Peak Drift (in.) and Approximate Performance
Light	C	0.46 <b>Minor</b>
Light	D <sub>1</sub>	1.02 <b>Moderate</b>
Light	D <sub>2</sub>	1.72 <b>Significant</b>
Veneer	C	1.29 <b>Moderate</b>
Veneer	D <sub>1</sub>	1.34 <b>Moderate</b>
Veneer	D <sub>2</sub>	2.21 <b>Significant</b>

Although the building mass increased significantly with the addition of brick veneer, the increase in drift ranged from moderate to slight. This is due to the *IRC* requirement for wood structural panel sheathing and hold-down devices for veneer in SDCs D<sub>1</sub> and D<sub>2</sub>. The analysis model differentiated between wood structural panel shear walls with and without hold-down devices so the different strength, stiffness, and deformation capacity were accounted for. Because of this, the *IRC* bracing required for brick veneer was seen to partially compensate for the increased demand.

The **above-code** measures were applied to the slab-on-grade base condition. The measures were seen to generally reduce the building drift, although drift increases were seen in a few walls due to changes in diaphragm rotation. In SDC D<sub>2</sub>, the approximate performance was improved by one category for all three **above-code** measures. In SDCs C and D<sub>1</sub>, significant decreases in drift were seen within an approximate performance category.

**Table A-4 Selected Results for Above-code Measures, Slab-on-grade Base Condition**

Above-code Recommendation	Walls	1 <sup>st</sup> Story Peak Drift (in.), Approximate Performance, and Maximum 1 <sup>st</sup> Story Drift Reduction		
		SDC C	SDC D <sub>1</sub>	SDC D <sub>2</sub>
Original Code Minimum	Light	0.5 Minor Damage	1.0 Moderate Damage	1.7 Significant Damage
Above-code Continuous Sheathing	Light	0.3 Minor Damage 39 percent	0.7 Moderate Damage 42 percent	1.2 Moderate Damage 30 percent
Above-code Hold-downs	Light	0.5 Minor Damage 28 percent	0.9 Moderate Damage 36 percent	1.0 Moderate Damage 47 percent
Above-code Lap on Rim Joist	Light	0.5 Minor Damage 6 percent	1.0 Moderate Damage 7 percent	1.4 Moderate Damage 24 percent

The cost of implementing each **above-code** measure during construction of the house was estimated in terms of percentage change to the construction cost for the basic house structure. Comparison to total house cost was not made because variations in finishes and fixtures can dramatically vary the house cost.

Use of continuous wood structural panel wall sheathing (fully sheathed) with overturning anchors in the corners of the house significantly reduced the drift in all Seismic Design Categories, and the approximate performance category was increased by one in SDC D<sub>2</sub>. The cost of making this change was estimated to be 9 to 10 percent of the cost of the structural portion of the model house used in this guide.

The addition of hold-down anchors at the ends of each full-height wall segment (at the corners and edges of each door and window) significantly reduced the drift in all Seismic Design

Categories, and the approximate performance category was increased by one step in SDC D<sub>2</sub>. For the model house, the cost of implementing this improvement was estimated to be 18 percent of the structural cost of the house.

Lapping wood structural panel wall sheathing over the band joist of the floors did not have a significant effect in SDC C or D<sub>1</sub> but did improve the approximate performance category by one in SDC D<sub>2</sub>. The cost of implementing this improvement was estimated to be 0.5 percent of the cost of the structural portion of the house. This **above-code** measure can be accomplished by either sheathing the wall with oversized panels (9-foot panels on an 8-foot wall) or cutting and blocking standard size sheets.

Use of the **above-code** measures in combination is thought to have a cumulative effect in improving performance and so is encouraged.

