Software for the Structural Design of Masonry

By Russell H. Brown, James K. Nelson, Jr. and Dennis Graber

Using software can free the design engineer from the drudgery of routine calculations and enable him to explore many more options, quickly and accurately. The capabilities of the fourth release of the structural masonry design software include design of masonry and precast concrete lintels, walls loaded out-of-plane, walls loaded in-plane (shear-walls) and columns. Wall and column elements can be designed by allowable stress design or strength design using the Masonry Standards Joint Committee Codes (1995, 1999, 2002 or 2005) and the IBC Codes (2000 and 2003). One major addition since Version 3 of the software is the addition of hollow clay unit masonry construction.

The engineer may specify the critical design forces, or may choose to have them calculated from specified design loads and dimensions. In the latter case, load combinations are calculated at very small intervals along the wall, and the critical design forces are determined and reported. Finally, printable documentation is provided for inclusion in design calculations that may be submitted to building officials or to archive designs.

Structural design of masonry can be tedious and complex, with so many choices available. Use of software allows the design professional to quickly determine designs that work, and therefore to try more options until an optimum solution is reached. Version 4.0 of the software for structural design of masonry is a significant improvement to the previous releases of the software. The new features include:
- Hollow Clay Unit Masonry (previously only concrete masonry was included),
- 2003 International Building Code has been added,
- 2005 MSJC Masonry Code has been added,
- Column Design including the following:
  o Interaction diagrams that are plotted with superimposed calculated axial load and bending moment,
  o Member forces can be calculated from specified load data,
  o Maximum and minimum reinforcing steel areas are calculated and compared to specified values,
  o P_{max} values are displayed (from slenderness and ρ_{max} provisions),
  o Shear design is performed. Ties are used as stirrups when needed, and required spacing is displayed.
- Lintel Deflection,
- Specified cover below the reinforcing steel,
- Lintel bar size choices have been expanded,
- Lintel Stirrups,
- Out of Plane wall deflection under service loads,
- Development lengths and splice lengths for bars selected are displayed
- Wall thicknesses of 14 inches and 16 inches for concrete masonry walls. and
- The ability to customize face shell and web thicknesses of the masonry units

The software is limited to hollow unit masonry, single wythe construction, but the masonry can be fully grouted or partially grouted (including ungrouted), and reinforcement may be included within grouted cells. The location of the reinforcing steel is specified by the design engineer and may be off center when an increase in effective depth is desired, as with retaining wall construction. Other modifications include a new *Design Basis* icon that combines all code selection and material properties into one location.

The Design Basis

Figure 1 shows the design codes tab in the design basis window. The building code, design criteria (strength design or allowable stress design), type of masonry (concrete or clay), concrete building code (for precast concrete lintels) and design criteria are selected on this tab.
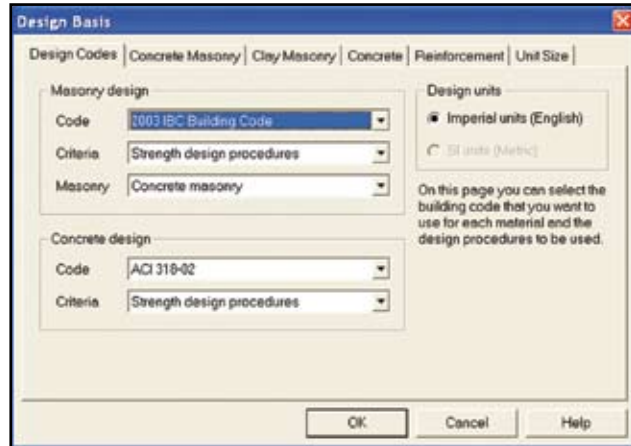

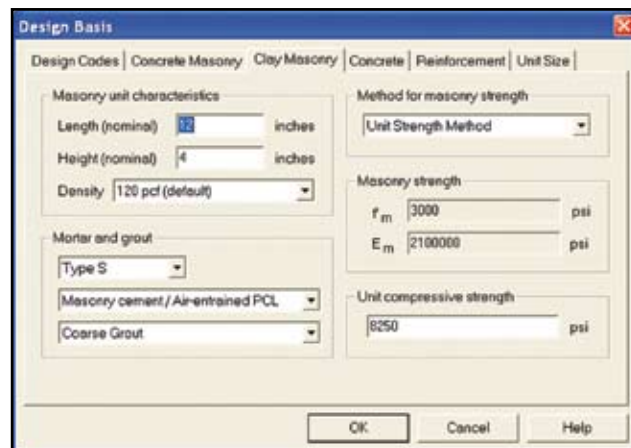*Figure 1: Design Basis - Building Code*

Figure 2: Clay Masonry Unit Properties

Figure 2 illustrates the options available for selecting hollow clay unit properties. The mortar used with clay masonry is also selected on this tab. The unit length and height are specified by the engineer, because the spacing of reinforcing steel depends on unit length and the height of masonry courses in lintels depends upon the unit height. Density of the material used in making the units is needed to calculate the weight of the masonry. Specified masonry compressive strength, f'_m, is entered by using either the unit strength method or the prism test method. In the unit strength method, it is not necessary to test prisms to determine compliance with f'_m, so it is most often used. In *Figure 2*, a unit strength of 8250 with Type S mortar results in f'_m of 3000 psi based on historical data.

The unit size is specified on the Unit Size tab shown in *Figure 3 (on next page)*. The default values correspond to the minimum face shell and web thicknesses required by the applicable ASTM Standard. Sometimes units with thicker face shells and webs are desired, such as for fire ratings or sound attenuation. The engineer can now take advantage of the additional material by increasing the default values.
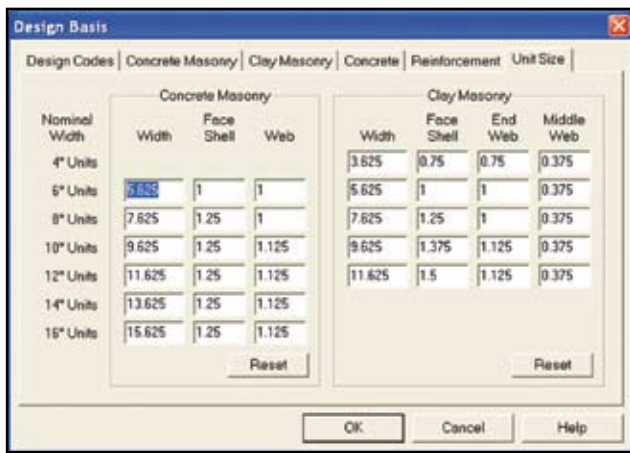
Figure 3: Design Basis – Unit Size

After specifying the design basis, the design engineer is ready to select the type of component to be designed — lintel, wall with out-of-plane loads, wall with in-plane loads (shear wall) or column. Using the "design" drop-down menu just over the left tool bar or by using the appropriate icon on the tool bar, the type of component is chosen.

Wall Design

Walls can be either reinforced or unreinforced. Strength design of walls loaded out of plane includes the P-Δ effect, including walls with boundary conditions other than simply supported. Graphical information makes it easy to quickly converge on an economical design. The software takes full advantage of code provisions that optimize the design by using the beneficial effects of axial load on the moment capacity. Partially grouted construction is included as an option in the software to minimize the amount of grout required in reinforced masonry construction. Shear walls can be designed with special end-zone reinforcement that greatly increases the bending capacity of the wall, with minimal increase in reinforcing steel area. Earth retaining structures can be designed with reinforcement placed off-center to optimize the capacity of retaining walls and basement walls.

If *Wall Design for Out-of-Plane Load* is selected, *Figure 4* will appear. The three tabs at the top of the window are Design Data, Construction Data and Load Data. Design Data includes the forces at the design section. The engineer can calculate these forces at the section assumed to control the design and specify them. Or, if the "Compute using load data" box is checked, the software will calculate the design forces based on information the engineer specifies on
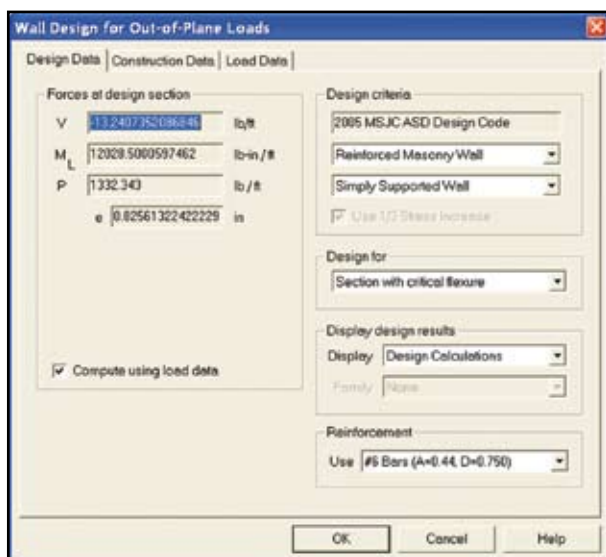

Figure 4: Design Calculations Output for Out-of-Plane Walls

this and other tabs in the Design window. In this mode, the software divides the wall into 100 increments along its height and designs for all required load combinations at each increment. This ensures that the critical design section and load combination is used in the final design. The engineer can select reinforced or unreinforced masonry and boundary conditions with the dropdown menu. Use of the ⅓ stress increase option button is limited to allowable stress design when Compute Using Load Data is not selected. Display options include Design Calculations, Interaction Diagram or Calculated Loads. When compute using loads is selected, the software automatically uses the ⅓ stress increase for load combinations for which it is permitted (MSJC ASD only).
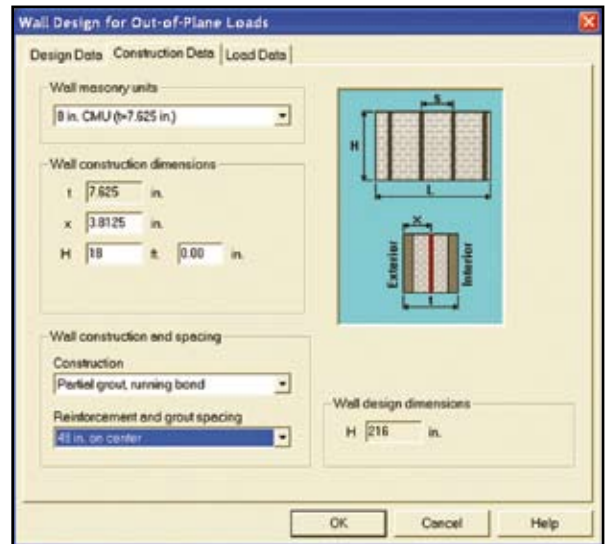

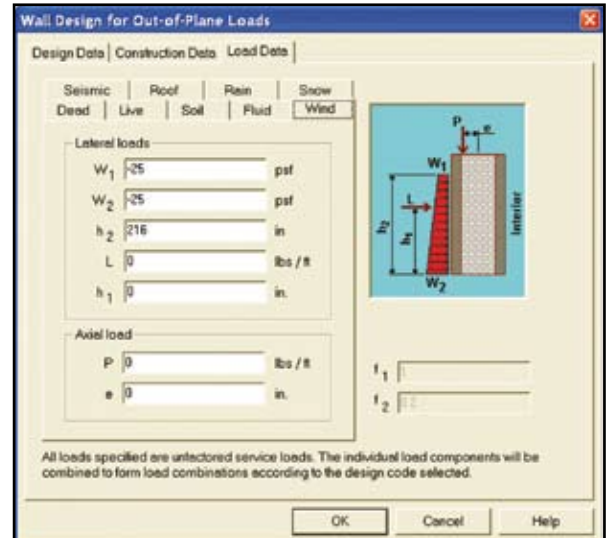Figure 5: Construction Data Tab for Walls Loaded Out-of-Plane

Figure 6: Load Data Tab for Out-of-Plane Wall Design

The Construction Data Tab (*Figure 5*) allows the engineer to specify the wall thickness, wall height, location of the reinforcement (centered or off-center), grouting (full or partial), bond pattern (running or stack), and horizontal spacing of reinforcing. Default values are recommended until an initial trial design is performed. Then these values can be changed quickly to arrive at an optimum design. Partial grout construction requires that only the cells receiving reinforcing be grouted. In the example shown in *Figure 5*, with a grout space of 48 inches, every 6th cell is grouted and the five cells in between are not. This can save significantly on grouting costs. Mortaring of the cross-webs is required adjacent to the grouted cells, however, and is included in the
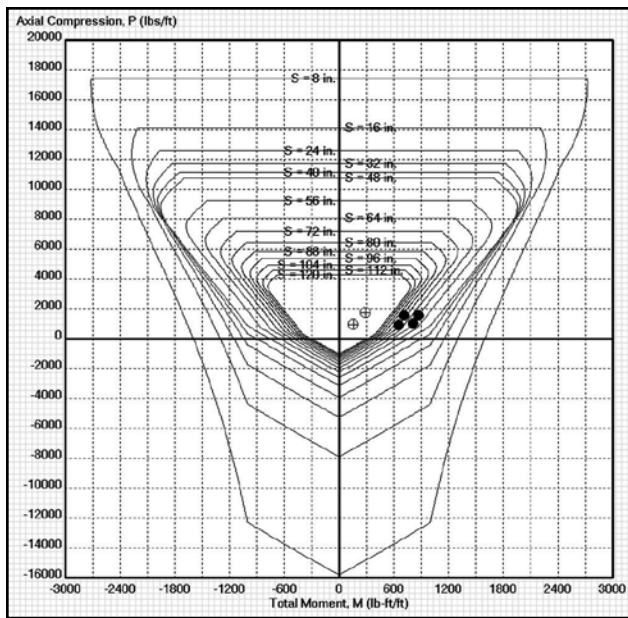
Figure 7: Interaction Diagram, Family of Curves

Figure 7A: Click "None" under Family to obtain a Single Interaction Diagram and Select Desired Reinforcement Spacing

section properties for analysis. The internal calculations for partially grouted construction are rigorous for these calculations. Performing such calculations by hand would be tedious and time-consuming, but the software does them almost instantaneously.

The value of x enables the engineer to locate the reinforcing steel within the wall. The default is in the center of the wall which is most common, since most lateral loads such as wind and earthquake are reversible. However, in cases of lateral loads from soil, placing the steel off center can result in significant savings.

If unreinforced masonry is selected from the Design Data tab, then another option in the Construction dropdown menu is ungrouted.

When a bar spacing is selected that exceeds six times the wall thickness or 72 inches, the software uses only that width in conjunction with a single bar to calculate the wall resistance. A message will appear to notify the engineer in this case.

The Load Data tab (*Figure 6*) permits the engineer to specify various loads (dead, live, wind, etc.). As shown in the inset drawing in *Figure 6*, loads can be axial (with or without eccentricity), lateral distributed loads (such as wind or earthquake), that can vary with height (as with earth retaining walls) and concentrated lateral loads. Loads can be positive or negative, especially wind and earthquake. The direction of the load shown in the inset in *Figure 6* is positive in the direction shown. Depending on the code selected and whether allowable stress design or strength design was selected, the software uses the appropriate set of load factors and load combinations to conduct the design.

If the interaction diagram was selected on the Design Data tab, it will be displayed. When Family is selected, the
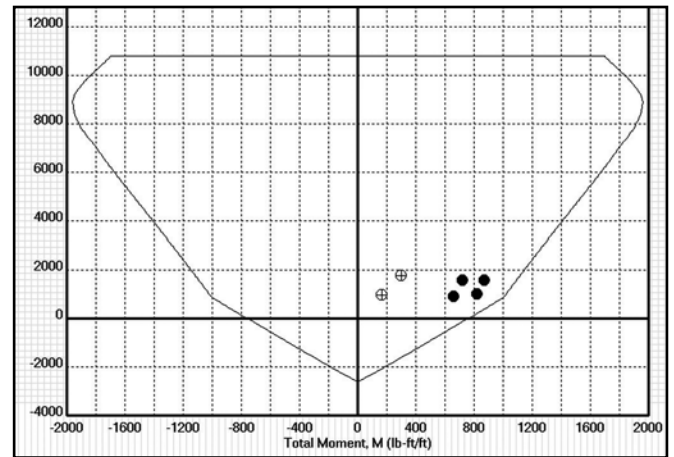
interaction diagram (*Figure 7*) allows the designer to quickly select the optimum bar spacing for the wall thickness selected. For example, in *Figure 7*, the different contours represent the interaction diagram for an 8 inch partially grouted wall with #6 bars. Each contour corresponds to a different bar spacing. The dots are the calculated or specified forces at the critical sections. By selecting the contour that encompasses all of the loading dots, an acceptable design for combined flexure and axial load results. The closer the dots are to the contour, the more optimum the design. Under Family, if none is selected, only the single bar spacing selected is shown in the interaction diagram (*Figure 7A*).

Prjct: Masonry Software Sample Output	Name: Russ Brown
Topic: Design of Out of Plan Wall	Date: 2006
Page:	Chkd: Jim Nelson

Design of a Reinforced Masonry Wall with Out-of-Plane Loads
Using the 2005 MSJC ASD Design Code

Material and Construction Data
    8in. CMU, Partial grout, running bond
    Wall Weight-41.03 psf
    Type S Masonry cement/Air-entrained PCL Mortar, Coarse Grout
    CMU Density-115pcf
    1"m-1500 psi (Specified)
    Em-900lm-1350000 psi

Wall Design Details
    Thickness - 7.625 in.
    Height - 216in. (Simply Supported Wall Effective height - H)
    x - 3.813 in.
    #6 Bars, Fy-60000.0
    Reinforcement Spacing - 48 in. On-Center

Wall Design Section Properties
    Ao - 1626 in.
    Io - 1328 in.
    So - 348.4 in.
    Ro - 2.858 in.

Wall Support: Simply Supported Wall
Specified Load Components

Load	P (lb)	e (in)	W1 (psf)	W2 (psf)	L (lb/ft)	h1 (in)	h2 (in)
Dead	1000	2	0	0	0	0	216
Live	800	2	0	0	0	0	216
Soil	0	0	0	0	0	0	216
Fluid	0	0	0	0	0	0	216
Wind	0	0	25	25	0	0	216
Seismic	0	0	20	20	0	0	216
Roof	0	0	0	0	0	0	216
Rain	0	0	0	0	0	0	216
Snow	0	0	0	0	0	0	216

Controlling Load Cases
Section Forces with Controlling Flexure
and Axial Load-D + W

    x/H - 0.550 from bottom of wall
    V - 13.24 lb/ft
    M_L - 12028.5lb-in./ft
    P - 1332 lb/ft at e_n- 0.8256 in
    M_T - M_L + Pe_n - 13128.5 lb-in/ft
    Moment Capacity - 16323.9 lb - in/ft (1350.33 lb-in/ft)
    at this axial load
    Shear Capacity - 1049.59 lb/ft

    The wall is adequate for these critical section forces.

Section Forces with Controlling Shearing Force - D + L + L$_r$ + S + R + W
    x/H - 0.000 from bottom of wall
    V - 241.7 lb/ft
    M_L - 0 lb-in./ft
    P - 2539 lb/ft at en - 0 in
    M_T - M_L + Pe_n - 0 lb- in/ft
    Moment Capacity - 18151.6 lb -in rt at this axial load
    Shear Capacity - 1049.59 lb/ft

    The wall is adequate for these critical section forces.

These were found to be load cases that controlled the design. The flexural, shear and axial forces shown are those occuring at the critical section for the case controlled by flexure and at the critical section for the case controlled by shear.

The following design calculations are for the section with controlling bending moment

Section Design Forces Used
    V - -13.24 lb/ft (Computed from Loads)
    M_L - 12028.5 lb-in./ft (Computed from Loads)
    P - 1332 lb/ft at e - 0.8256 in (Computed from Loads)

Computed Design Values
    Note: ⅓ stress increase was used
    Effective Width - 48in.
    Web Width - 8.313 in. on effective width

    Allowable Shearing Force - 1050 lb/ft
    The wall is adequate in shear

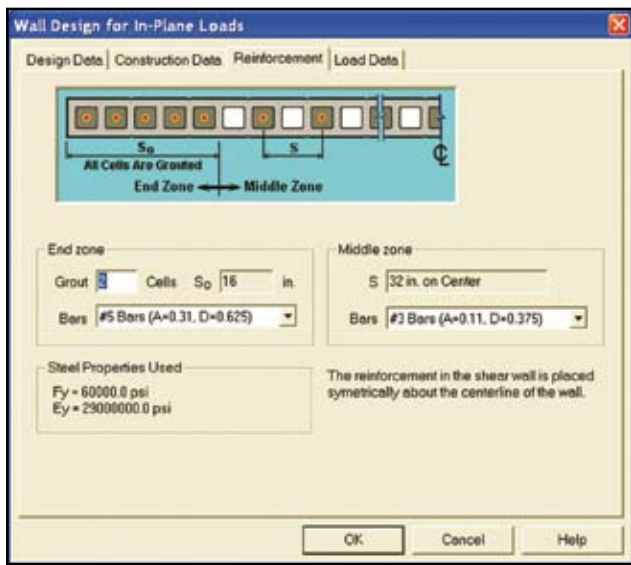Figure 8: Design Calculations Output for Out-of-Plane Walls

Figure 9: Reinforcement Tab for Shear Wall Design

Clearly, all of the loading dots fall within the contour for the 48-inch spacing selected.

If no satisfactory contour is displayed, the engineer can either select different bar sizes or different wall thicknesses. When a satisfactory wall design is determined from the interaction diagram, the Design Calculation display can be selected. The information on the design calculation page is intended to provide the engineer with more detailed information, including shear design and reinforcing bar development and splice lengths. Specified design data is presented in a format intended to be suitable for submitting to building officials. Files can be easily saved electronically as well. A sample design calculation page is shown in *Figure 8 (on previous page)*.

If *Wall Design for In-Plane Load* and the reinforcement tab are selected, *Figure 9* will appear. An end zone can be included in a shear wall to increase its moment carrying capacity with little increase in reinforcing steel. Reinforcing steel placed in such an end zone is subjected to higher stress than interior bars, and these steel forces have a larger lever arm than those for interior bars. End zone steel significantly increases moment capacity, with little impact on the maximum area of reinforcement limitations in strength design and in the allowable stress design provisions of 2003 IBC. All of the cells in the end zone are reinforced, and grouted whereas cells in the middle zone can be partially grouted and reinforced with different sized bars.

Figure 10: Load Data Tab for Shear Wall Design

Loading for shear walls is specified in the window displayed when the Load Data tab is selected (*Figure 10*). The engineer specifies the shearing force, the bending moment and the axial load at the top of the shear wall and the software internally calculates the forces at other locations. Walls with openings are not included in the design. However, a pier between two openings can be designed as a shear wall if the forces are determined using some other method, such as a finite element program. After all information is entered, the interaction diagram can be displayed to determine if the wall has adequate capacity. *Figure 11* illustrates such a diagram. Since all of the loading "dots" fall inside the interaction diagram, the wall is satisfactory for flexure and axial loads. The horizontal line at an axial force of 120 kips is the maximum axial load associated with the maximum steel area provisions of the code. None of the dots (loads) are permitted to be above this line.

Once a design is found that satisfies the interaction diagram, select design calculations on the design data tab, and *Figure 12* is displayed. Only a portion of the design calculation output is shown in this figure. The critical loading combination and location for flexure and axial load are shown along with the applied loads and capacities. The same information is also shown for the critical shear case. When shear reinforcing is needed, suggested horizontal bar sizes and spacings are also displayed.
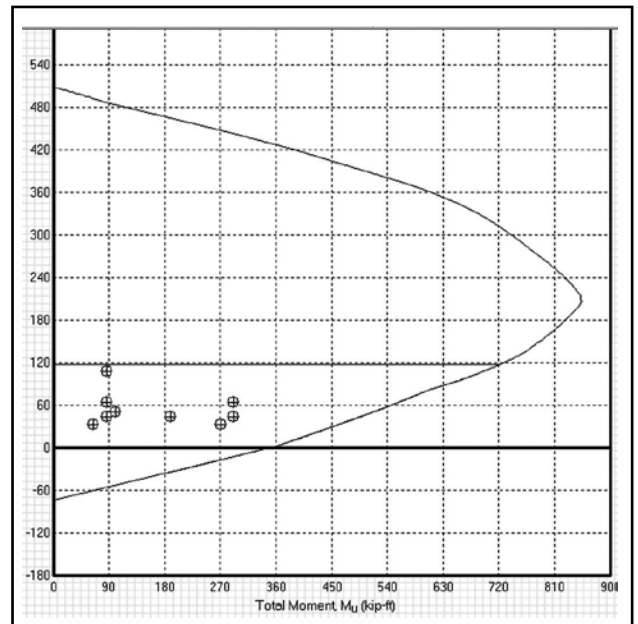

Figure 11: Interaction Diagram for Shear Wall

Lintel Design

Lintels also can be designed according to the MSJC codes (1995, 1999, 2002 or 2005), the IBC Code (2000, 2003) or, in the case of reinforced concrete lintels, ACI 318 (1999 or 2002) Code. As with walls, the critical shearing force and bending moment can be entered directly or the software can compute them from specified load data and dimensions. Stirrups can be used in the new version of the software to resist shear forces if the masonry or concrete alone is not sufficient. Lintel deflections are also calculated for service dead and live loads.

Column Design

The new column provisions are similar to those for shear wall design. The engineer can specify up to eight layers of reinforcing steel in a concrete masonry or clay masonry column. Allowable stress design and strength design procedures are supported, and code provisions such as maximum axial load or maximum steel area are calculated. Interaction diagrams can be displayed and compared to calculated
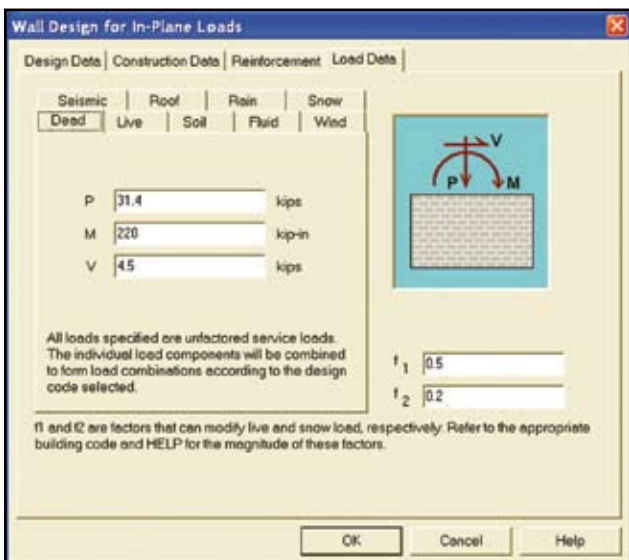
axial loads and bending moments. The shearing force capacity is also calculated and compared to calculated design shearing forces. If needed, shear reinforcement (in the form of column ties) can be used to resist shear forces.

Summary

Software to structurally design masonry has been updated to include hollow clay unit masonry, masonry column design and the newest building codes (IBC 2003 and MSJC 2005). New features also include the addition of stirrups as a design option for lintels, calculation of lintel deflections, user control over reinforcement location in lintels, the calculation of development and splice lengths for reinforcing bars, and service load level P-Δ deflections for walls loaded out of plane. Anticipated release date is April 15, 2006 (**www.ncma.org**).▪

Dr. Nelson is the Brazzel Professor of Engineering at the University of Texas at Tyler, and Chair of the Department of Civil and Environmental Engineering. He teaches courses in the area of structural analysis and design and has been involved in the development of engineering design software for many years.

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Dr. Brown is a Professor of Civil Engineering at Clemson University and chaired the Flexure and Axial Loads Subcommittee of the Masonry Standards Joint Committee during the 2005 Code Cycle. He is a Founding Member and Fellow of The Masonry Society and Fellow of American Society for Testing and Materials.

Controlling load case for bending moment: 0.9D + 1.2F + 1.6H + 1.6W
Controlling x/H ratio for bending moment: 0
M_u = 2464 kip-in (205.33 kip-ft)
V_u = 16 kips
P_u = 31.8557 kips
M = 1540 kip-in (128.333 kip-ft)
V = 10 kips
P = 21.2371 kips
Controlling bending moment capacity: 5,468.87 kip-in (455.74 kip-ft)

Controlling load case for shearing force: 0.9D + 1.2F +1.6H + 1.6W
Controlling x/H ratio for shearing force: 0.23
M_u = 1934.08 kip-in (161.173 kip-ft)
V_u = 16 kips
P_u = 30.7389 kips
M = 1208.8 kip-in (100.733 kip-ft)
V = 10 kips
P = 20.4926 kips

The following design calculations are for the section with controlling bending moment

Section Design Forces Used
   P_u = 31.86 kips
   M_u = 2464 kip-in
   V_u = 16 kips
   P = 21.24 kips
   M = 1540 kip-in
   V = 10 kips

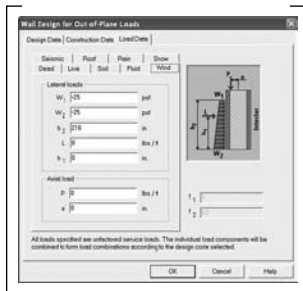Wall Flexural Design Data
   P_b = 332.2 kips (C_b = 63.47 in)
   Maximum P_n = 625.5 kips (Section 2108.9.5.4)
   Maximum Available P_u = 0.65(625.5) = 406.6 kips (Section 2108.9.5.4)

Figure 12: Design Calculation Output for Shear Wall