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CANADIAN SOFTWARE FOR THE STRUCTURAL DESIGN OF ENGINEERED MASONRY

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ABSTRACT
Masonry Analysis Structural Systems (MASS™) is a design software package which designs masonry beams, out of plane walls, and shear walls in accordance with current CSA standards. The objective from the inception of the software development process has been to provide structural engineers an effective and transparent design tool which still leaves the responsibility of engineering judgement to the user. The engineer needs only enter general assemblage geometry and apply unfactored loads and MASS™ will calculate critical load combinations for bending moment, deflection, and shear. The software then iterates through hundreds of possible assemblage cross-sections, based on the inputs of the user in an attempt to satisfy ultimate and serviceability requirements. Additional effort has been made toward minimizing the cost of construction for the designed assemblage by incrementally increasing unit size, strength, reinforcement spacing, and reinforcement size. The recent release of MASS™ Version 3.0 will transition all existing MASS™ designs in their current scope into compliance with the new CSA S304-14 standard. The upcoming Version 3.1 release will introduce the Chapter 16 seismic considerations to shear wall design as well as the addition of a multi-storey shear wall module.

KEYWORDS: *software, design, algorithm, interaction diagram, analysis*

INTRODUCTION
Masonry Analysis Structural Systems (MASS) is an engineering software package which assists the user in designing individual elements of a masonry structure. The software features four distinct modules which are programed to design masonry beams, out-of-plane walls, shear wall elements, and shear walls with openings and movement joints. Versions 3.0 and newer will design assemblages in accordance to CSA S304-14 standard [1] while previous software editions used the CSA S304.1-04 standard. The majority of the MASS™ user base is made up of practicing

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engineers; however, MASS™ is also a valuable teaching tool for undergraduate and graduate students looking to familiarize themselves with masonry design.

ROLE WITHIN THE ENGINEERING PROCESS

The role of MASS™ within the engineering design process is to perform design calculations for individual structural masonry members. Requiring only assemblage's geometry and unfactored loads, MASS™ applies all possible load combination in the National Building Code of Canada [2] and designs based on those inputs.

Decisions involving engineering judgement are left to the engineer while the software handles the calculations which are performed the exact same way each time where each step can be sourced back directly to a building code or masonry standard. For example, MASS™ will not assign end fixities to an out-of-plane wall design since this involves professional judgement. However, it will distribute loads within that wall once the user has specified those end conditions. MASS™ will also not determine exactly how a wall adjacent to an opening will resist the transferred vertical load since this is not clearly described in CSA S304 [1], however it will design that wall element once the user has distributed that load to the sections they determine to be appropriate.

Importance of User Proficiency

A phrase is frequently used to emphasize the importance of underlying assumptions behind the inputs entered into any design software: "*garbage in, garbage out*". MASS™ is a tool to be used at the discretion of the engineer, saving time while performing the same calculations and analysis as they would otherwise perform manually.

The design results produced by MASS™ are only as good as the fundamental assumptions behind the user inputs. For example, if the user incorrectly assumes a restrained fixity at the top of a wall where the roof would not provide enough rotational support, the software will produce results that are incorrect, even though internally it has correctly performed all design calculations with a fixed end condition at the top of the wall.

Assumptions that are made during the design process may need to be re-examined and updated when other information changes. For example, the axial load applied to a shear wall from the storey above might be based on a self-weight that was calculated based on a 15cm unit grouted every fourth cell. Through the course of the design process, it might be later determined that the wall needs to be constructed using a larger unit in order to have adequate moment resistance and therefore the design is changed to a 20cm unit grouted every fifth cell. Since the self-weight from the storey above is applied as a static value based on user input, it is up to the engineer to recognize this change and adjust the magnitude of the self-weight resting on the bottom storey. Seismic loading may also need to be updated since the loading is affected by the weight of the structure. Using a different size unit or grouting pattern than the one used to determine mean that the engineer must go back and make the appropriate adjustments. The engineer is ultimately responsible for checking and verifying all assumptions to ensure that they remain correct throughout the design process.

Transparent Design Methodology

Offering complete transparency of internal processes and intermediate calculations to the end user is an essential feature of MASS™. This allows the engineering community to easily confirm design outputs and makes it a more useful as a teaching tool to individuals seeking to become proficient in masonry design.

Figure 1 a) shows the *Simplified Results* output upon the completion of the software's design process. This output contains a general overview of the results which includes a summary of factored loads and resistances as well as and other useful data such as the neutral axis location, reinforcement placement, or the critical load combination according to the National Building Code of Canada. Figure 1 b) shows the *Detailed Results* output for the same design. Here, the user can use the additional information to compare software output with hand calculations since it features a comprehensive list of variables along with corresponding descriptions, formulas, results, and code references.

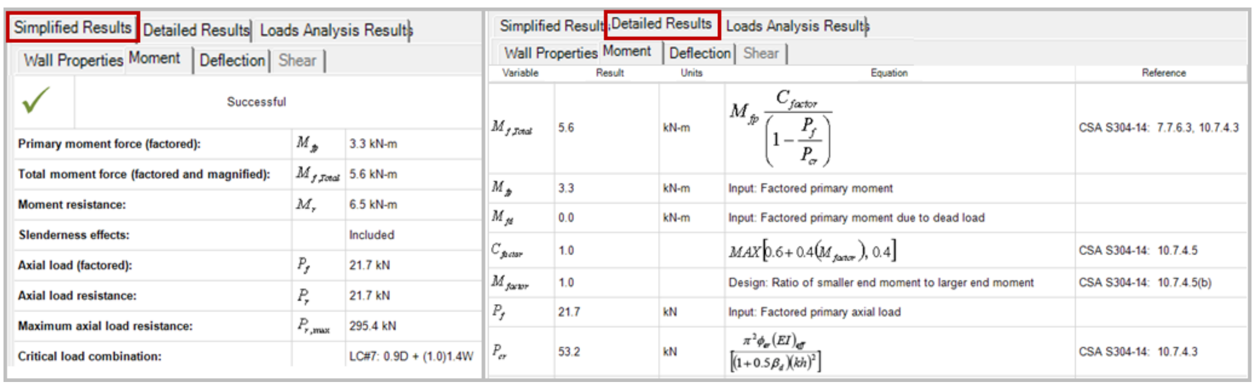


Figure 1: MASS™ outputs a) Simplified Results, and b) Detailed Results

ANALYZING MASONRY FROM A SOFTWARE PERSPECTIVE

MASS™ determines whether a design is successful or unsuccessful by first assuming a preliminary masonry assemblage cross-section and then checking it against several criteria found in the CSA S304-14 [1] and NBCC [2]. Many of these checks are simple binary inquiries. Checking minimum steel requirements is an example of one the more basic inquires, involving a comparison between the area of steel present within the wall and the code-complaint value. If the area of steel is not satisfied then MASS™ returns a failure message; otherwise, the design passes on to the next criteria.

An example of a considerably more rigorous failure criterion is checking the moment resistance for an out-of-plane wall, given several permutations of load combinations and failure mechanisms. The software tests this failure criteria by developing an interaction diagram between axial load and bending moment (P-M interaction diagram) and then comparing the total factored moment, $M_{f,tot}$, to the moment resistance, M_r, at the same axial load. Figure 2, shows this comparison completed for nine load combinations with added labels to load combinations 2 and 4.

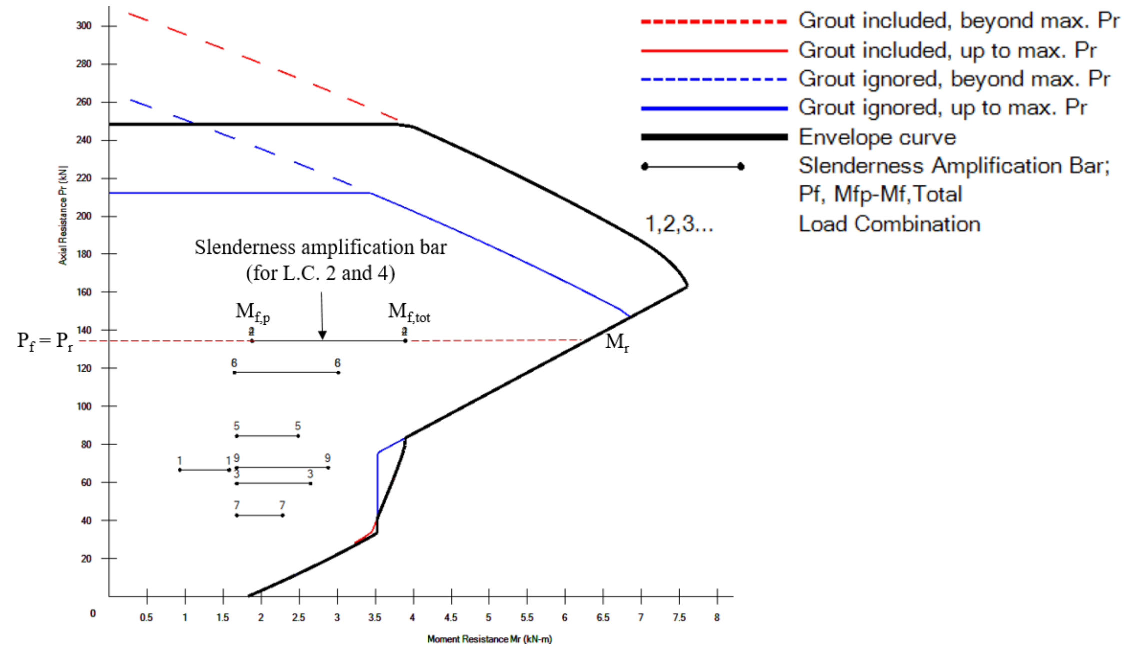


Figure 2: Passing design where M_r is greater than $M_{f,tot}$ at the same axial load

The horizontal lines, or slenderness amplification bars, are shown to graphically depict the result of slenderness effects on the design in accordance with clauses 7.7.6.3 and 10.7.4.3 [1]. The left point is the primary factored moment, $M_{f,p}$ and the right point is $M_{f,tot}$ after slenderness has been taken into account. The moment resistance criteria is satisfied if each slenderness amplification bar lies entirely within the envelope curve.

Determining Critical Load Combinations

Each load combination is plotted and numbered on one P-M interaction diagram. There is no need to identify at the outset which combinations are most critical as they are all examined equally. However a critical load combination is chosen based on the highest ratio of $M_{f,tot}$ to M_r to simplify the reported results. Figure 2 shows that while the highest total factored moment is load combinations 2 and 4 at 3.9 kN·m, its ratio of $M_{f,tot}$ to M_r of 0.62 is less than that of load combination 9 which has a $M_{f,tot}$ to M_r ratio of 0.76. As a result, it is designated as being critical and all simplified results are displayed for load combination 9.

SOFTWARE PROCESS FOR GENERATING THE INTERACTION DIAGRAM

The envelope curves on P-M interaction diagrams generated by MASS™ are created dynamically and take every assemblage cross-sectional property into account. The calculation procedure and resulting envelope curves are dependent on whether the masonry is un-grouted, partially grouted, or fully grouted and if the wall is reinforced. The interaction diagram must be continuous in order to plot moment resistances for all possible axial load values. The software achieves this by considering all possible failure mechanisms to determine which is governing for each axial load.

Interaction Diagram for an Unreinforced Wall

The envelope on a P-M diagram for an unreinforced wall is created in accordance to three clauses in CSA S304-14 [1]:

1. 7.2.2: Moment resistance at ultimate failure conditions is based upon the equivalent rectangular stress block analysis.
2. 7.2.3: The wall is only permitted to crack if the eccentricity is less than the limiting eccentricity of 0.33 times the wall thickness.
3. 7.2.4: When the wall must remain uncracked, moment resistance is governed by either tensile or compressive stress exceeding the maximum allowable under linear elastic analysis.

The eccentricity of each load combination is first compared to the allowable limit to determine which type of analysis is valid. Figure 3 shows the limiting eccentricity, or e_{limit} line, plotted on an interaction diagram. A cracked section analysis is valid only if the load combination is located above the e_{limit} .

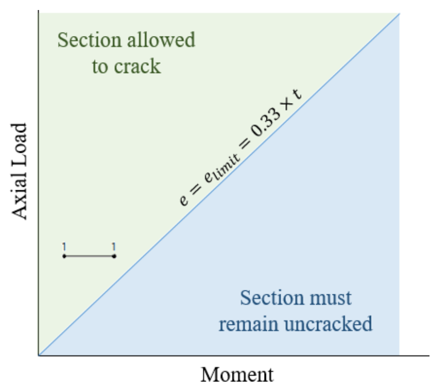


Figure 3: Wall loaded under Load Combination 1 above the e_{limit} line, allowed to crack

Cracked analysis

When a wall is cracked, MASS™ uses the lesser of two moment resistance values in determining the moment resisting capacity. The first is based on assuming a neutral axis location and determining the resulting equivalent rectangular masonry stress block. The net axial force and moment resisted by the wall are calculated and stored using force and moment equilibrium. MASS™ then assumes a new neutral axis location and iterates until the neutral axis location places the entire wall cross-section within the compression zone.

The second moment resistance is based on the eccentricity reaching the e_{limit} line. MASS™ plots this line by multiplying the axial load by e_{limit}. This process is repeated starting at 0kN and terminates when the axial load reaches to the maximum axial load. Once both the e_{limit} line and the cracked section at ultimate failure have been calculated, MASS™ then uses the lesser of the two values as the moment resistance for a given axial load.

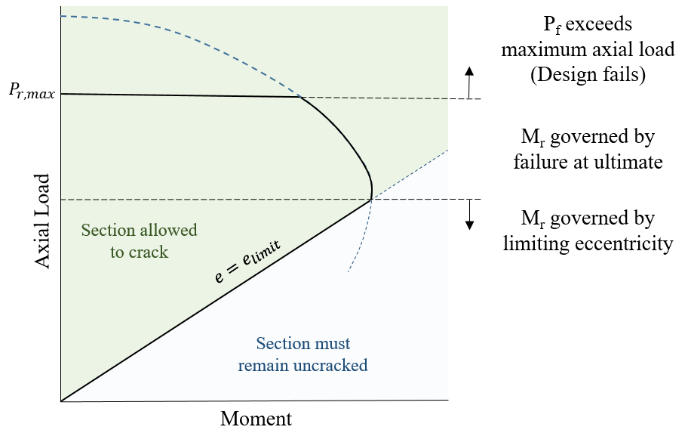


Figure 4: Envelope curve using cracked section at ultimate conditions

CSA S304-14: 7.4 [1] does not allow walls to be loaded beyond 80% of its full axial capacity. MASS™ reflects this requirement by cutting off the top portion of the interaction diagram, as shown in Figure 4.

Uncracked analysis

The entire area beneath the e_{limit} line must be designed using linear elastic behaviour. MASS™ analyzes the assemblage using two criteria for this region of the P-M interaction diagram: cracking on the tension face of the wall, and reaching a compressive stress that exceeds the linear elastic range for masonry.

Transitioning from linear elastic to being governed by the limiting eccentricity

To avoid underestimating the strength of the wall, MASS™ draws a line straight upward from the point of intersection between the tension and compression controlled relationships. The axial load and moment where these relationships intersect is saved as P_{equal} and M_{equal}. The intersection of the vertical line with the e_{limit} line can then be determined by dividing M_{equal} by the limiting eccentricity. Moment resistance begins to be governed by the e_{limit} line for axial loads above this intersection, seen in Figure 5.

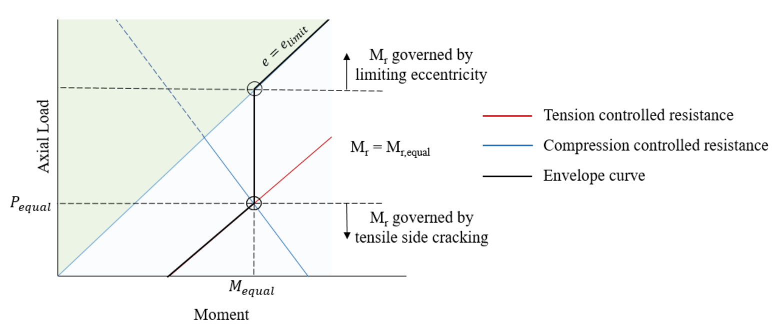
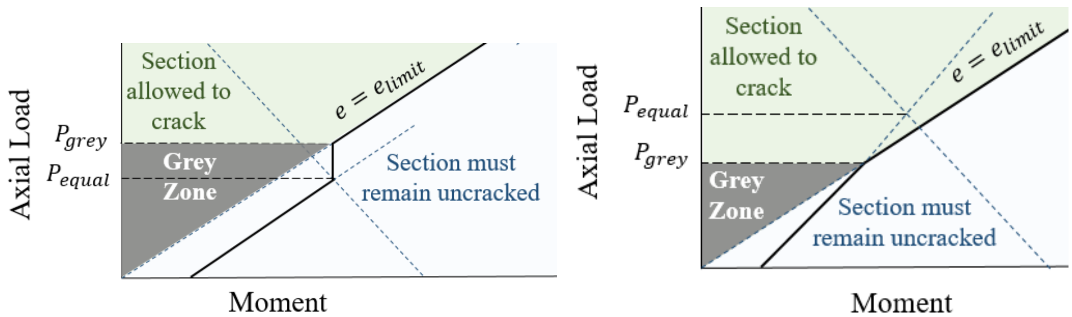


Figure 5: Envelope curve based on uncracked wall

The Grey Zone – Cracked section loading with uncracked section resistance

It is possible for factored loads to be located within the cracked portion of the interaction diagram while M_r is still based on uncracked section analysis. This region to the left of the e_{limit} line where there is a higher uncracked moment resistance than cracked resistance is referred to as the grey zone. Figure 6 a) shows the location of the grey zone when P_{equal} is less than P_{grey} while Figure 6 b) shows its location when P_{equal} is less than P_{grey}.



(a) (b)

Figure 6: Location of grey zone on P-M diagram a) P_{equal} less than P_{grey} b) P_{equal} greater than P_{grey}

REINFORCED MASONRY INTERACTION DIAGRAM

The P-M interaction diagram for reinforced masonry walls follows the same procedure as the cracked section analysis. MASS™ starts by assuming a neutral axis location to determine the corresponding moment capacity using strain compatibility, and equilibrium. The initial iteration assumes the neutral axis, c, is located 1mm from the compression face of the wall and incrementally increases the distance to the neutral axis until the entire wall is contained within the equivalent rectangular masonry stress block.

Ignoring and including the effects of grout

The presence of grout in a masonry wall has no effect on its moment resistance while the equivalent rectangular stress block is contained within the face shell. The compressive strength is reduced from $f'_{m,hollow}$ to $f'_{m,grouted}$ when the compression zone exceeds the thickness of the face shell. This also reduces both the corresponding P_r and M_r. MASS™ then completes a second analysis for each strain profile which also ignores the effects of grout since it can be reasonably assumed that the addition of grout to a wall design should not reduce the wall's capacity. Figure 7 shows the effects of including or ignoring grout on the resulting interaction diagram for a wall constructed with 15 cm, 15 MPa units and an assumed neutral axis of 33mm from the compression face.

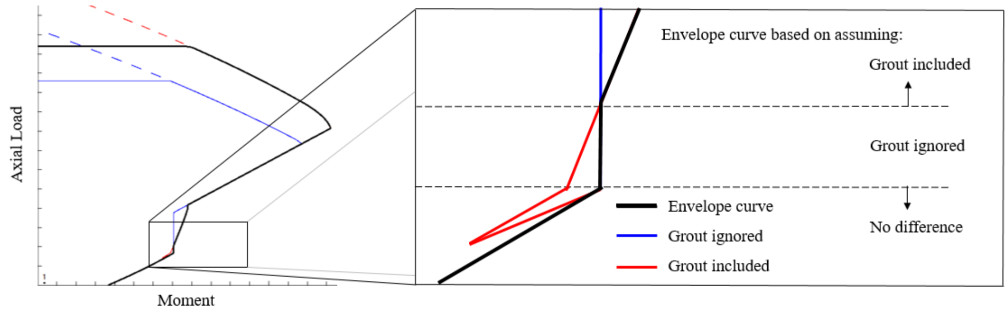


Figure 7: Regions of interaction diagram where grout is included or ignored

While the strain profile is the same for both scenarios, the divergence in P_f and M_f values originates from the difference in strength used in the equivalent rectangular masonry stress block. The compressive strength of the grouted masonry assemblage, $f'_{m,grouted}$, drops from 10MPa to 7.5 MPa when the compression zone is no longer within the face shell, because a portion of the compression zone includes the grouted region. The same strain profile ignores the effects of grout and uses a smaller compression zone (face shell area only) which allows for the use of higher ungrouted compressive masonry strength, $f'_{m,hollow}$. This results in higher values for P_r and M_r.

Transitioning from reinforced to "unreinforced"

The steel is no longer in tension once the neutral axis reaches the reinforcement. MASS™ then treats the wall as if it were unreinforced since the steel is ignored in compression. This results in two major transitions on the P-M interaction diagram that can cause discontinuities in the plotted line.

The first transition is the limiting eccentricity, e_{limit}, which applies to unreinforced walls and walls containing reinforcement that is not in tension. It governs all moment resistances based on strain profiles that result in an eccentricity that exceeds e_{limit}. The second is the result of clause 10.6.1 [1] which states that where there is reinforcement in tension coupled with masonry in compression, the width of the compression zone, b_{eff}, shall be the lesser of the spacing between bars and four times the thickness of the wall. A large shift occurs at the transition where the steel is no longer in tension because it is at that point where the entire length of wall can be used for the compression zone. Figure 8 shows the transition for a 15cm unit with vertical reinforcement spaced every 1200mm.

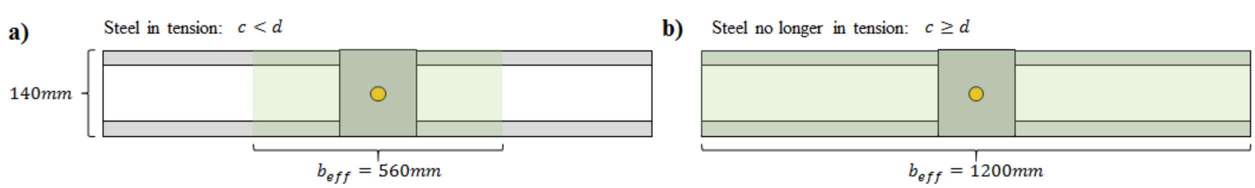


Figure 8: Effective compression width when a) steel in tension and b) when steel not in tension

The discontinuity created by the sudden jump in b_{eff} can be accommodated by linear interpolation between the two points. Load combinations with a value of P_f between the tension and compression transition points may have a M_r magnitude based on these values. However, any point with an axial load above the compression transition point are compared to and limited by the e_{limit} line. Figure 9 shows how MASS™ handles this by implementing logic which categorizes an interaction diagram based on the location of the transition points relative to one another.

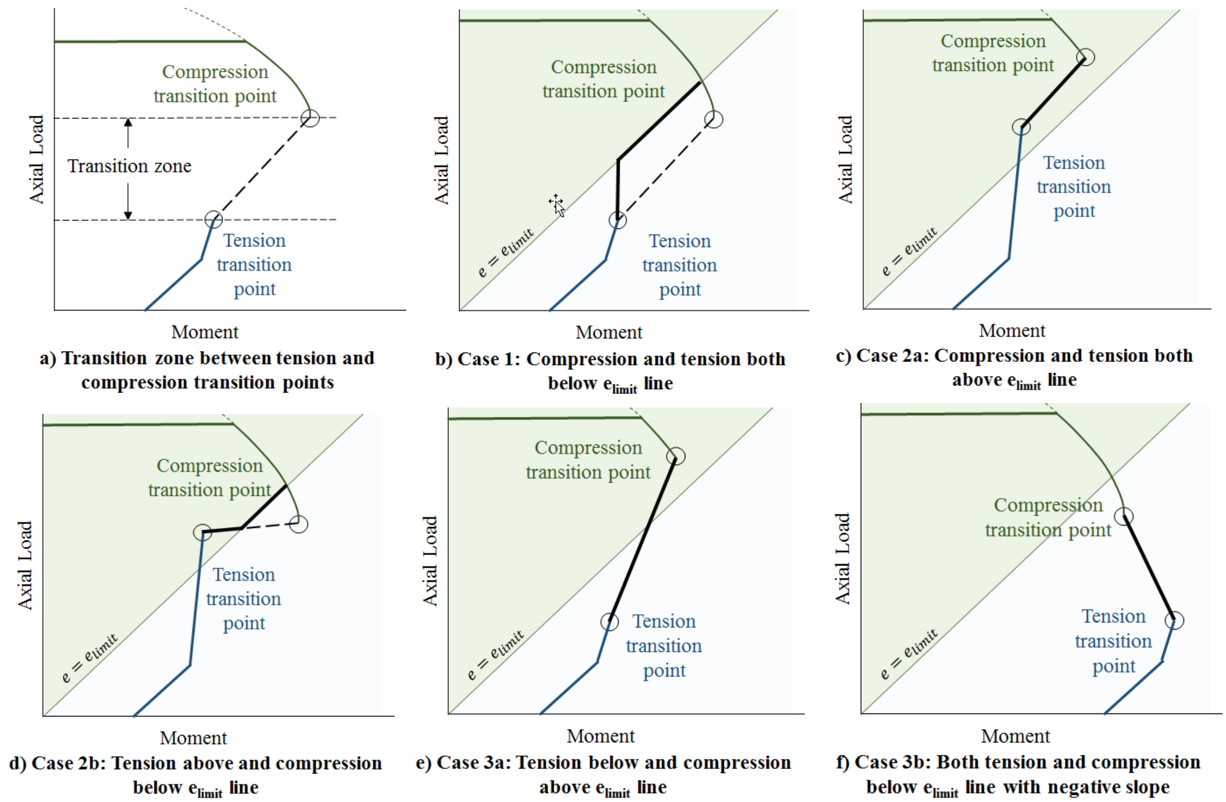


Figure 9: Transition zone with envelope curve cases

As is the case for unreinforced walls, the maximum axial load cannot exceed 80% of the axial load in full section compression. An added case for reinforced walls is considered when the height-to-thickness ratio exceeds 30 based on clause 10.7.4.6.4 [1].

SOFTWARE DESIGN ALGORITHM

MASS™ arrives at a successful design using a brute force method of iterative analysis and incrementally adjusting cross-section properties upon not meeting a given failure criterion. The software stops and displays the calculations and results when MASS™ analyzes a section that passes all design criteria. Alternatively, MASS™ displays the results for the last attempted design when none of the sections allowed by a given set of user inputs are successful.

There are multiple selection options for each assemblage property that is incremented during the design process, resulting in hundreds of possible permutations to be analyzed. The user can choose which values are considered for each property in the design process by using the input check-boxes to enable and disable block sizes, strengths, and reinforcement bar size and spacing. Figure 10 shows the selections which are enabled by default for an out-of-plane wall assemblage where the properties used for the successful design are highlighted in green. The default property selections result in up to 500 unique cross sections to be analyzed. This includes 20 unreinforced plus 20 reinforced wall sections, each featuring 24 potential reinforcement arrangements.

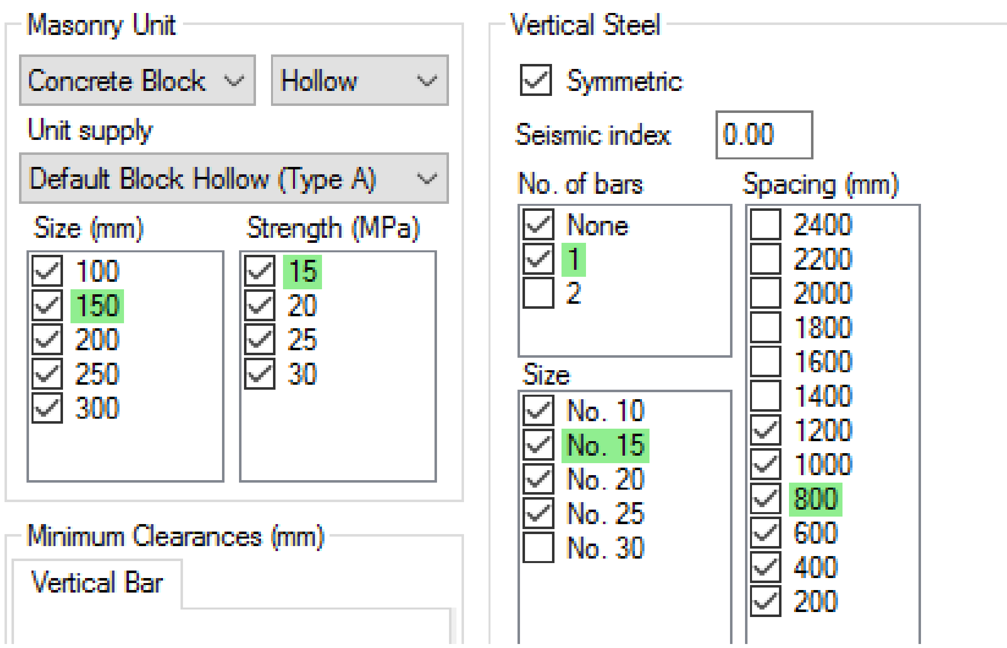


Figure 10: MASS™ input window with default property selections used for design.

The successful design result displayed for the user is also the first section analyzed that does not trigger any failure criteria. Since there can be multiple possibilities for a successful solution, an additional algorithm was developed to prioritize certain designs over others by defining the order in which each unique cross section is analyzed. This was accomplished by dividing each of the incremented properties into hierarchies, where some are incremented before others with the main objective of minimizing the cost of construction. However, as every project is priced differently, there is no universal estimating formula that can be used to make the definitively claim of providing the design with the lowest cost of construction.

MASS™ first attempts designs using smaller units before selecting a larger one because they are assumed to cost less. This is also true for unit strengths or reinforcement areas. MASS™ first attempts a design using the smallest masonry unit with the lowest strength which contains the least amount of reinforcement. If a successful design is not found, the reinforcement is increased before changing the block strength or size. The logic used by MASS™ follows the flowchart in Figure 11 which establishes which properties are changed following a failed design.

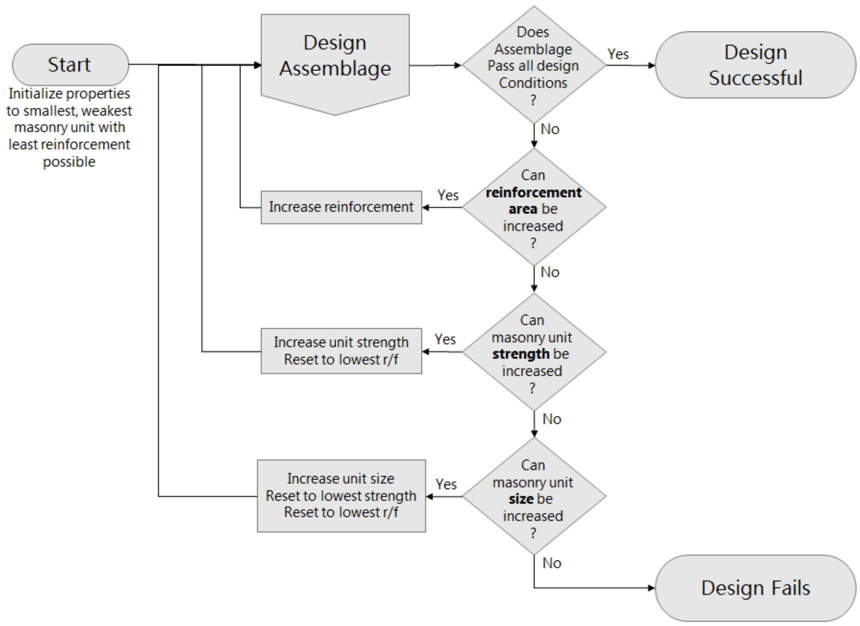


Figure 11: Logic used for the MASS™ design process

The design algorithm ensures that for each MASS™ design result, an increased property is not used without first attempting all design configurations beneath it. For example, a successful design using a 25cm, 15MPa unit has already attempted every possible design using 10cm, 15cm, and 20cm units, each using 15, 20, 25, and 30MPa block strengths, and for each of those size and block size and strength combinations.

Upcoming Releases

At the time of submission (Feb, 2017), the newest available official release of MASS™ is Version 2.2. This is the final edition of the software to use the 2004 CSA masonry standards. Version 3.0 has currently been made available as an official release candidate for engineers looking to design in accordance with the newer 2014 masonry standards. Many of the common issues from the 2004 CSA S304.1 have been addressed and implemented in Version 3.0. This includes a complete overhaul of masonry beam design to more closely resemble that of reinforced concrete. Future releases of MASS™ currently in development will include Chapter 16 of the S304-14 [1] as well as multi-storey shear wall design.

ACKNOWLEDGEMENTS

The MASS™ software is the result of a joint partnership between Canada Masonry Design Centre and Canadian Concrete Masonry Producers Association.

REFERENCES

[1] CSA S304-14, *Design of masonry structures*, Canadian Standards Association, Mississauga, Ontario, Canada, 2014

[2] NNCC 2015, *National Building Code of Canada 2015*, National Research Council, Ottawa, Ontario, Canada, 2016