# Canadian Long Span Earth Covered Magazines – Design Challenges

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**Abstract**

Canadian Long Span Earth Covered Magazine (CLSECM) has unique structural dimensions such as large column-free span of about 17 m. This poses considerable design challenge in that the inter-magazine distance (IMD) and the blast load have to be adjusted, as the design is governed by the long span roof and not the headwall/door assembly, as usually observed in ECMs with lesser spans. Blast loads have to be determined from test results based on specific IMD, instead of the standard 7bar/3 bar load criteria for standard IMD spacing, as listed in NATO and other publications. Customized IMD and the associated blast load ensures achievement of an optimum blast hardened CLSECM design, without undue compromise on real estate acquisition for siting of the CLSECM cluster (rear-front and side-side configuration). The initial design, done in late 80s, was based on SDOF analysis using decoupled components of CLSECM. Recent evaluation of the design, completed in 2016, is based on modern Finite Element tool like LS-DYNA using integrated components of CLSECM, and demonstrates the conservatism inherent in the simplified approach that required many assumptions. Regardless of the structural adequacy of the CLSECM in its current configuration, it has also been evaluated for the classification of 7bar/3bar ECM standard, since this classification is employed for Quantity-Distance criteria for siting and licensing purposes, a demand worth proper examination from blast engineering design perspectives.

**Keywords:** Earth Covered Concrete Magazine, Long Span Concrete Roof, Blast Load Design, Single Degree of Freedom Analysis, Finite Element Analysis (LS DYNA), Earth Covered Magazine Bar Rating, Earth fill overlap

## Introduction

Ammunition storage facilities in the Canadian Forces Ammunition Depots (CFADs) date back to the days of the Second World War. Most of these magazines for storing Ammunition and Explosives (A&E) were found to be deficient in many respects and did not meet the requirements of safety, security, shelter, operation and long term warehousing. Consequently, in the early 1990's, the Department of National Defence (DND) embarked on a magazine replacement program with the development of standard magazines to accommodate the long term warehousing requirements, maximize storage efficiency and improve safety & operations. The following design requirements were prescribed for the development of standard Earth Covered Magazine (ECM), to allow for varying storage capacity with minimal design/construction adjustments. This led to the development of Canadian Long Span Earth Covered Magazine (CLSECM), designed by departmental engineers. These were then site-adapted later by external Consultants at various locations, as required. However, it must be emphasized that the DND inventory still continues to accommodate other types of less structurally glamorous storage magazines, which are planned to be assessed under the Ammo Safety Compliance Program.

## Design/Construction Requirements

CLSECM design/construction features meet the following requirements:

### Safety

- The structure should resist all normal loads such as its own weight, earth, snow and live loads on roof and lateral earth pressures on walls.
- An accidental explosion within one magazine i.e. the donor (Potential Explosion Site – PES) should not result in propagation of detonation in adjacent magazines i.e. the acceptors (Exposed Site – ES). The PES is not expected to survive the internal accidental explosion. In addition, there is no specific requirement to protect or limit the level of damage to the ES, except to prevent sympathetic detonation of its explosive contents.

- Blast, fragments and fire associated with an accidental explosion within a PES should not pose a significant hazard to other inhabited structures and public traffic routes in the vicinity.
- Stored materials should be protected from direct hits from fragments, debris and lobbed ammunition items including damage from animals, forced entry, vandalism etc.

**Security**

- Unauthorized access to the stored materials should be prevented.
- Each magazine is to be provided with an intrusion detection and alarm system.

**Shelter**

- Materials and their packaging should be protected from moisture induced degradation.
- Materials should be sheltered from extremes of temperature fluctuations.
- The structure should protect its contents from external fire, lightning strikes etc.

**Operation**

- Storage area should be optimized, allowing for appropriate vertical clearance to provide for long term stacking height of Five (5) pallets.
- Operating aisle should allow for the use of 2-ton fork lift trucks inside for warehousing
- Doors should be wide enough to accommodate the entry/exit of ammunition loaded trailers (flatbed trucks) into the structure.
- Smooth transition from the apron exterior to the structure interior floor is essential for the operation of warehousing vehicles.

**Special features**

- Design standard for ECM should be such that only the front-rear (Length) dimension can be adjusted when needed, as the intention is to accommodate varying storage capacity of A&E requiring different volumes.
- All other dimensions (Width and Height) should not vary except for minor adjustments from warehousing perspectives, including the provision of a column-free clear space of about 17 m wide, based on the layout of ammunition pallets and fire & access aisles.

**Engineering highlights of CLSECM**

Based on the above requirements, the following Two Standard types of Canadian Long Span Earth Covered Magazines (CLSECMs) were developed and designed by departmental engineers, in the early 1990s. Later CLSECMs are site-adapted versions, designed by external Consultants, engaged through independent contracts *(Figs. 1a -1d)*

- *Large variant CLSECM* with clear dimensions of 17,100 mm wide x 28,750 mm long and 5,700 mm high. This can house a maximum NEQ of 250,000 kg of equivalent TNT of HD 1.1 from design considerations. A clear door opening of 5000 mm wide x 3100 mm high provides access for warehousing vehicles and equipment.
- *Small variant CLSECM* with clear dimensions of 17,100 mm wide x 18,000 mm long and 4200 mm high. This can house a maximum NEQ of 40,000 kg of equivalent TNT of HD 1.1 from design considerations. A clear door opening of 4000 mm wide x 3100 mm high provides access for warehousing vehicles and equipment
- Later site adaptation of the Small variant was built with minor adjustments to accommodate NEQ of 45,000 kg of equivalent TNT of HD 1.1 from design considerations. This version has clear dimensions of 15,850 mm wide x 17,890 mm long and 6170 mm high. This design employs a gantry crane system for warehousing operations instead of fork-lift operations, thus resulting in increased height.
- Currently, DND inventory consists of 18 Large variant and 22 Small variant CLSECMs, apart from other types of storage magazines
- Since the designs are based on equivalent TNT, actual amount of storage of different types of explosives is to be adjusted in accordance with the appropriate TNT equivalency factors
- Flat roofed CLSECMs with long clear span *(Fig. 1e)* consist of a heavily reinforced roof (average 850 mm thick) and walls (600 mm thick) with 600 mm of earth cover on roof, compacted to 80% Proctor density, while the side and rear walls are covered with earth fill at 1:3 slope, compacted to 95% Proctor density, to allow for easier maintenance of earth slopes.
- Since the ends of roof slab and wall section are permitted to rotate within 2 to 4 degrees for blast loads, double leg stirrups are placed in a staggered fashion throughout to ensure post-elastic behaviour.

- The large sliding door is made up of horizontally spaced steel wide-flanged sections sandwiched between steel plates. The original design door is operated manually using pulley system while it is electrically operated in later versions
*(Fig. 1f)*
- The electrical wiring cables fastened to the roof slab and wall are provided with slack in the cable wiring to accommodate large deformations of CLSECM components from blast loading.
- Fire aisles and sufficient clearances are provided all around between the ammunition pallet and the roof/wall components to allow for plastic deformation of components
- An exterior annex structure in reinforced concrete is attached to the front wing wall to house the mechanical and electrical equipment. This structure is not designed for blast loads

This paper briefly highlights the issues and challenges surrounding the original design of CLSECM and, the recent (2016) verification of the structural adequacy of CLSECM, based on the latest standards and practices in designing ECMs.

**Original Design (Early 1990s)**

While the structural analysis of CLSECM for conventional loads was quite straight forward based on the National Building Code of Canada, design and analysis for accidental blast loads was challenging due to the following reasons:

- A literature survey of ECMs designed and constructed in the NATO member countries, prior to the commencement of CLSECM design, indicated that:

- The roof span of ECMs was about half as that of the CLSECM.
- Design NEQs were smaller than that of the CLSECM storage capacity
- There was no consistency in the evaluation of blast loads and the prescribed load in the prevailing NATO AC 258 standard, predecessor of AC 326 and the current AASTP-1, was limited to the head wall/door, as this was deemed to be the critical component for ECM design
- ECMs were also spaced at "Standard Inter-Magazine Scaled Distances" in meters (0.8 $m/kg^{1/3}$ rear/front or front/rear and 0.5 $m/kg^{1/3}$ side to side)
- The above separation distances are meant to ensure that the blast load on the head wall/door assembly did not exceed those prescribed in the prevailing Standard (7 bar on the head wall and roof),
- Given the immense structural dimensions and the large span roof of CLSECM, the application or extrapolation of the prevailing NATO and other standards, raised concerns for the design of CLSECM. A heavy roof to resist the prescribed blast load would only add to the conventional loads, requiring further increase in roof strength. Hence, it seemed prudent that an optimized design can be attempted by diminishing the blast hardening of ES by increasing the Scaled distance between PES and ES to reduce the blast effects on ES. However, no Standard, guidelines or tools were available at the time to address this strategy. Consequently, the expertise of late Dr. Wilfred Baker of Baker Engineering, USA, an eminent authority on blast physics and author of many publications, was solicited to provide guidance in determining the design blast loads for the CLSECM for varying Scaled distances, different from the prescribed Scaled distances.

- Dr. Baker concluded that the results, obtained from laboratory model ECMs listed in the BRL MR2680 report and scaled results from the full scale Eskimo test series, represented the State of the Art on blast loads from ECMs and could be extrapolated for determining the blast loads on CLSECM. He constructed the necessary Pressure-Distance and Scaled Impulse-Distance diagrams to enable the determination of loads on CLSECM components for varying Scaled distances
*(Figs 2a -2b)*

- An optimum Inter-Magazine Scaled Distance (IMD) layout was then chosen, based on Dr. Baker’s curves, for designing both the Large and Small variant CLSECMs to ensure that the magnitude of blast loads were reasonable and not excessive for resistance by various components. The following shows a comparison of the design scaled distances between CLSECM design and the prevailing NATO & Other standards for regular ECMs:

| *Type of ECM* | *Design Scaled distance (front-rear/rear-front) – m/kg $^{1/3}$* | *Design Scaled distance (side-side) - m/kg $^{1/3}$* |
|---|---|---|
| Regular ECMs | 0.8 | 0.5 |
| Large variant CLSECM | 1.4 | 0.6 |
| Small variant CLSECM | 1.1 | 0.6 |

- Based on the above increased Scaled distances, critical blast loads were determined for each CLSECM component while allowing for any CLSECM to act as the PES in the CLSECM cluster of side-side and front-rear/Rear-front orientations. For each component, the worst case scenario of PES-ES combination was chosen for design blast loads. In some instances, the "As-Built" scaled distances were greater than the above "Design" values due to site conditions, thus reducing the blast effects even further.

- Each component was then designed to resist the combination of both conventional and accidental blast loads using the Single Degree of Freedom (SDOF) analysis and employing the design procedures described in the US publication, TM5-1300 – Structures to resist the effects of accidental explosions, predecessor of UFC 3-340-02. Component responses were limited to the recommended values in this publication for Protection Category 3.

- *Figs 3a – 3b* show typical structural details of the Large variant CLSECM

- The following extract from the more recent NATO publication "PFP(AC/256-SG 5&6)D(2010)0001 - Nationally Approved Structures for Explosives Areas", rightfully provides for an optimized design of ECM by striking a balance between PES-ES separation distance and blast hardening of ES.

*"When design environment criteria are available as continuous functions of net explosives quantity and distance from the Potential Explosion Site (PES), there is complete freedom to choose both the distance and the type of construction in order to obtain the most economical solution. Design and construction are based on analytical calculations supported by model or full-scale tests. The construction may be used over the full range proved by the calculations. Modifications may be made provided the design environment criteria are taken into account"*

This principle was adopted in the design of CLSECM to account for the large roof span. No field or model test have been conducted so far to validate the theoretical design. However, a more rigorous analytical approach was pursued recently to re-assess the design, as described hereunder.

**Design verification and ECM-Bar classification (2016)**

Although the CLSECMs have been functioning well in a rigorous Canadian climate, questions arose about the structural soundness of the 25 year old departmental design and subsequent site adaptations meeting present day ECM standard design requirements, for the following reasons:

- Substantial amount of research, field & laboratory tests and other design considerations may have evolved since the original design, particularly in the determination of blast load effects on ECMs from surrounding ECMs and the development of sophisticated tools for structural analysis.

- Existing Standards normally classify ECMs as 3 bar, 7 bar and Undefined, based on the blast resistant capacity of the head wall from accidental explosions from surrounding ECMs. This classification is also used by the Explosives Safety and Licensing authority in the Department of National Defence, Canada. Interesting to note that such bar rating criteria is not imposed on the design of non-earth covered magazines.

- Since the CLSECM design loads for blast were determined for specific scaled distances, unlike the Standard ECM design, they were not Bar-rated and thus posed challenges during siting and licensing purposes, in accordance with the Quantity-Distance Tables recommended by NATO and Canadian standards.

- Hence, in late 2016, it seemed prudent to launch an independent assessment of the structural soundness of CLSECM and its validity in meeting present day standards including the most recent research information and tools available for the design of ECMs. The study also included the determination of Bar-classification for CLSECMs to facilitate the use of QD tables for siting and licensing purposes.

Prior to conducting the design verification study, a literature search of the published standards was undertaken including contacts with a number of international subject matter experts (SMEs) in the area of explosive safety design of ECMs. The literature study and SME discussions concluded that the following documents can be considered as current standards/guidelines and tools for the design and siting of ECMs:

- **USA**
  DoD Manual 6055.09-M – US DoD Ammunition and Explosives Safety Standards, Volume 2, Explosives Safety Construction Criteria, February 20, 2008, Administratively Reissued August 4, 2010.

- **UK**
  JSP 482, MOD Explosives Safety Regulations, UK, May 2013.

- **UNITED NATIONS**
  International Ammunition Technical Guidelines (IATG) Series 01-12 – UNSaferGuard.

- **NATO**
  AASTP – 1 - Manual of NATO Safety Principles for the Storage of Military Ammunition and Explosives, May 2006.

- **CANADA**
  In general, Canadian standards and practice with respect to Explosives Safety Regulations follow the NATO recommendations.

A comparative study of these documents indicate that, while similarities exist in areas of blast pressure and impulse on various ECM components including design scaled distances for ECMs *(Table 1)*, some differences also exist between them. In addition, the above standards/guidelines require standard IMDs for the applicability of the corresponding blast pressure and impulse on various components of ECM. Since CLSECM configuration of IMDs does not conform to this arrangement, the blast effects had to be determined from other sources.

After research, it is determined that the best available tool for obtaining the blast loads is:
"Blast Effects Computer- Version 7.0 (BEC 7.0)", commissioned by US DoD, but only authorized as a research tool at the present time and not as a design tool. A similar tool has also been sponsored by NATO using the same BEC model "Explosives Safety Risk Analysis, Part II: Technical Background," NATO Standard AASTP-4, Edition 1 Version 4, September 2016. Both tools provide essentially the same results.

BEC 7.0 is an EXCEL based tool, developed from the best fit curves using extensive experimental data that includes all known tests on ECMs, some dating back to the 1950s. These tests also include both flat-roofed and arched structures, incorporating a range of different loading densities in PES (Ratio of charge weight to magazine volume) and different amounts of soil overburden, details of which are well explained in the publication:
"DDESB Blast Effects Computer, Version 7, User's Manual and Documentation," Technical Paper No. 17, Rev. 2, Department of Defense Explosives Safety Board, Alexandria, VA, December 2016.

Validity of the application of BEC 7.0 curves for CLSECM, is further examined from additional considerations such as a) flat-roofed data versus arched data, b) variations in loading density and c) potential for increased blast suppression perspectives from heavy structural skin of CLSECM compared to those included in the BEC 7.0 dataset *(Table 2)*

The report (Ref. 4) provides detailed analysis of these factors but suffice to mention that no adjustments are finally recommended due to number of uncertainties and dissimilarities between the BEC 7.0 dataset and CLSECM structural engineering features.

Various PES-ES load combinations are considered to obtain the worst possible blast loading scenario on the ES structure, based on the BEC 7.0 tool *(Figs. 4a-4b).* Three different Finite Element Models (FEM) using the sophisticated LS-DYNA software are used for the non-linear dynamic analysis/design verification of CLSECM structure, each addressing different structural component. The first model relates to the response of the roof slab and the other two models examine the response of side wall, and the headwall/ door assembly. Representing the entire structure in a single 3D-model was not deemed necessary due to the prohibitive size of the model and run time. Consequently, the approach chosen using partially integrated components, as described above, is considered adequate to provide good fidelity for the structural response of interest and a significant improvement in analytical accuracy over the SDOF models used in the original design.
*(Figs 5a-5d & 6a-6c).*

Consistent with the guidance in UFC 3-340-02, a safety factor of 1.2 is applied to the NEQ prior in calculating the pressure and impulse using BEC. This safety factor is used for all the design load cases in conjunction with the response criteria for Protective Category Level 2, though Level 3 is quite admissible for ECM design. Detailed description of the FEM models, boundary conditions, loading scenario and dynamic response of CLSECM components is well explained in the Report (Ref 4). Report also describes the results obtained for various loading conditions including the conventional loads with animated graphic images of component response.

Regardless of the actual configuration of the CLSECM cluster and their blast resistant capacity for maximum NEQ, they are also evaluated for ECM Bar classification rating, based on the worst possible loading scenario extracted from present day standards/guidelines *(Tables 3, 4 & 5)*. This evaluation is done to assist the siting and licensing authority, who rely on the practice of employing Quantity-Distance criteria for Bar rated ECMs. Needless to state, that CLSECMs are unlikely to be subjected to the higher Bar rating loads, as they are configured at separation distances far greater than the standard IMDs, as noted above. This study concluded the following:

- Small Variant CLSECMs meet the 7-bar classification for ECMs.
- Large Variant CLSECMs meet the 3 bar classification for ECMs. While all structural components meet the 7 bar load, the sliding door assembly fails due to shear inadequacy in the webs of the horizontal wide-flanged beams due to larger door opening than the Small variant.

Finally. *Table 6* provides a comparative summary of the "blast loads and the associated component response" between the original design and the latest design verification of the CLSECM, including the response to the "ECM standard bar-rating loads".

**Impact of earth fill overlap between CLSECMs, located side-side**

Sometimes, the earth fill between side-side siting of CLSECMs at standard scaled distance of 0.5 (D3) results in overlap to varying heights, due to uneven topography and flatter slopes as constructed in CLSECM (Fig 7)

In such instances, Canadian Licensing Criteria, based on NATO recommendations, require adjustments to side-side Scaled distance to ensure that the design storage quantity of NEQ can be maintained, as indicated below (metric):

No change in Design Scaled distance at 0.5 (D3) – if overlap is less than ½ H (height of structure)
Increase Design Scaled distance to 0.8 (D4) - if overlap is greater than ½ H but less than ¾ H
Increase Design Scaled distance to 1.1 (D5) – if overlap is greater than ¾ H.

This QD imposition drastically reduces the design storage quantity of A&E, if the overlap QD criteria is to be followed. However, this requirement also appears to be in conflict with the ECM design criteria, which only requires a minimum side-side Scaled distance of 0.5 (D3). Important to note that such a requirement is not mandated in other publications related to ECM design/siting such as: "DoD 4145.26-M DoD Contractor's Safety Manual for Ammunition and Explosives", which permits total solid earth fill between side-side ECMs without restrictions on the design NEQ.

Regardless of the above differences, study is underway to examine the impact of solid earth fill (worst case scenario) between CLECMs on the overall structural integrity and design storage capacity. This study is to be performed by

a) considering twin CLSECMs located side by side at D3 Scaled distance
b) determining the internal blast effects from PES and,
c) analyzing the impact of blast loads transmitted through the solid earth fill on the structural integrity of the side wall of ES, the most critical component for this scenario.

The results of this engineering analysis, soon to be completed, would either confirm or deny the need for QD adjustments from licensing perspectives.

**Remedial Measures for Large variant CLSECM Door Upgrade**

While currently there is no urgency to upgrade the large variant CLSECM to 7 bar ECM, a remedial solution has been determined so that the door does not fail in shear for the 7 bar loading.

Door upgrade proposal adopts the following principles:

- reduction of shear force to acceptable limits by reducing the clear span of the door; however, span reduction should not impede/restrict access of warehousing vehicles and equipment.
- retrofit measures should avoid or minimize interference with existing structure/operations as much as possible
- work should be carried without disturbing the storage contents as much as possible
- material used for retrofit should be compatible with existing construction

This is achieved by attaching 400 mm thick precast concrete extension blocks to the pilasters on either side of the door to reduce the clear opening *(Figs. 8a-8c). (Figs. 9a & 9b)* show rotation at the ends of door for various thicknesses of concrete blocks and the force to be resisted by the attachment of blocks. Once the retrofit is completed, “Large variant CLSECM” will also meet the 7 bar rating standard *(Fig 10).* Any future PES facilities, constructed in the vicinity, can then be sited at appropriate QD separation distances.

**P-I diagram for CLSECM**

The assessment also includes the development of Pressure – Impulse (PI) diagrams for the various components of CLSECM including the PI envelope for the whole CLSECM. These diagrams are beneficial to readily assess the structural adequacy of CLSECM for various combinations of IMDs and NEQs *(Fig. 11*)

**Conclusions**

1. CLSECMs, designed about 25 years ago using limited data on blast loading and simplified analytical tools such as “Single Degree of Freedom” analysis on de-coupled individual components of ECM, could result in overdesign with reserve capacity, as noted from the use of more sophisticated tools for the estimation of blast loads, structural analysis and design.

2. CLSECMs are sited at scaled distances different from those prescribed in standard publications to achieve an optimum design, particularly for the large span roof slab. Consequently, blast loads are determined based on the non-standard separation distances and not on bar rating loads specified for standard separation distances.

3. Recent design verification assessment of CLSECM using integrated components without decoupling and employing sophisticated analytical tools (LSDYNA), confirms the overdesign inherent in the simplified approach.

4. CLSECMs, as built, in their existing configuration layout and structural details, are structurally sound to meet present day standards/guidelines on ECM design.

5. CLSECMs, when assessed for ECM Bar classification standard, the following has been concluded:

- Small Variant CLSECMs meet the 7-bar classification for ECMs.

- Large Variant CLSECMs meet the 3 bar classification for ECMs due to shear inadequacy of the sliding door assembly.

6. ECM design criteria and ECM QD criteria require re-examination for purposes of consistency, due to differences in various publications, referenced herein this paper. The demand for Bar-rated design requirement of ECMs should also be reviewed to allow for flexibility to achieve optimum design by balancing separation distance (IMD) and blast hardening of ECM structure *(Ref 6)*.

# Appendix

Fig. 1a - Small Variant CLSECM cluster

Fig. 1b - Large Variant CLSECM cluster

Fig. 1c - CLSECM in summer environment with Annex Structure in the front

Fig. 1d - CLSECM in winter environment

Fig. 1e - CLSECM interior view with large clear space and closed door

Fig. 1f - CLSECM – Sliding door assembly with pulley system

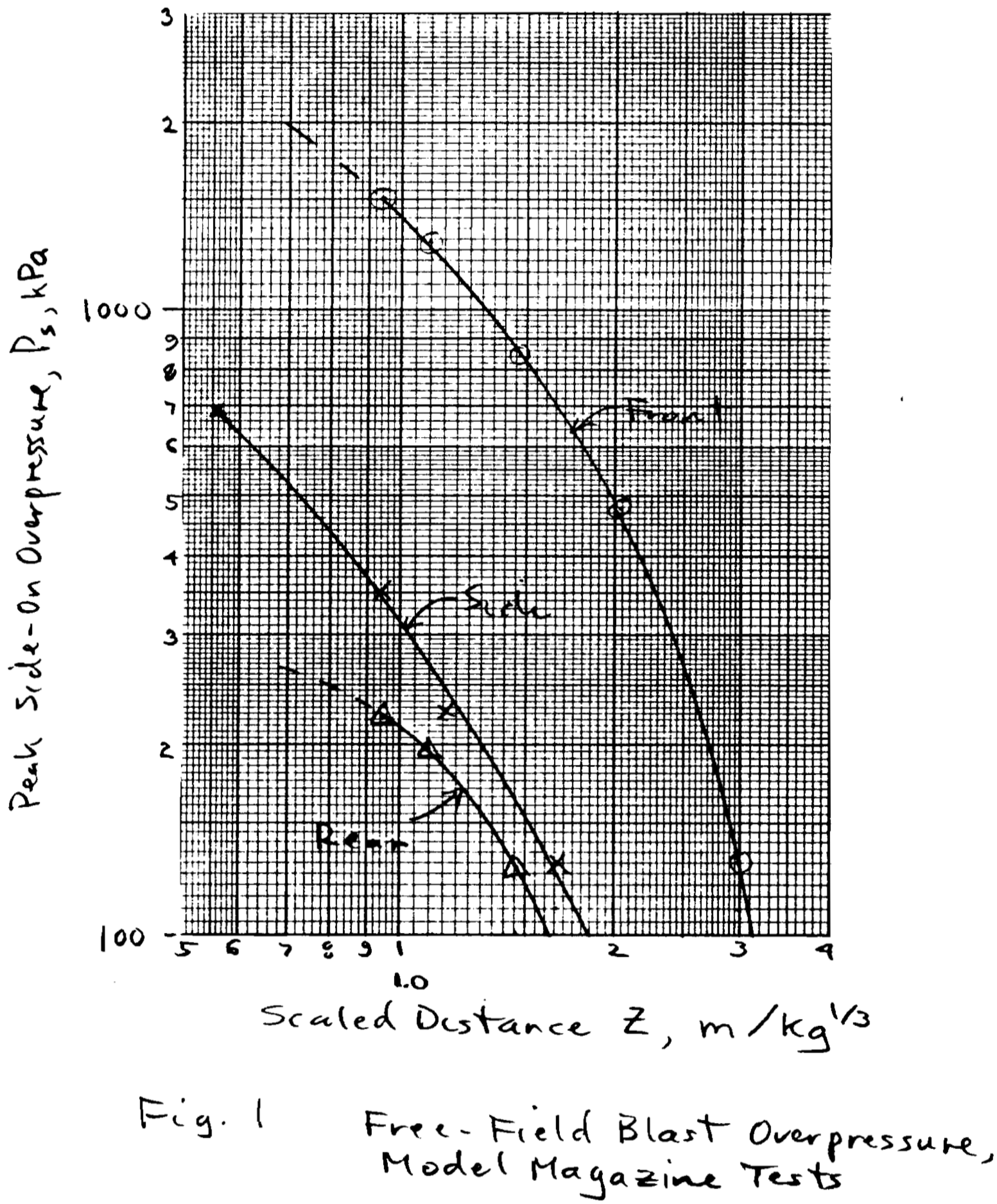



Fig. 2a - Blast pressure-Scaled Distance curves developed by Dr. Baker

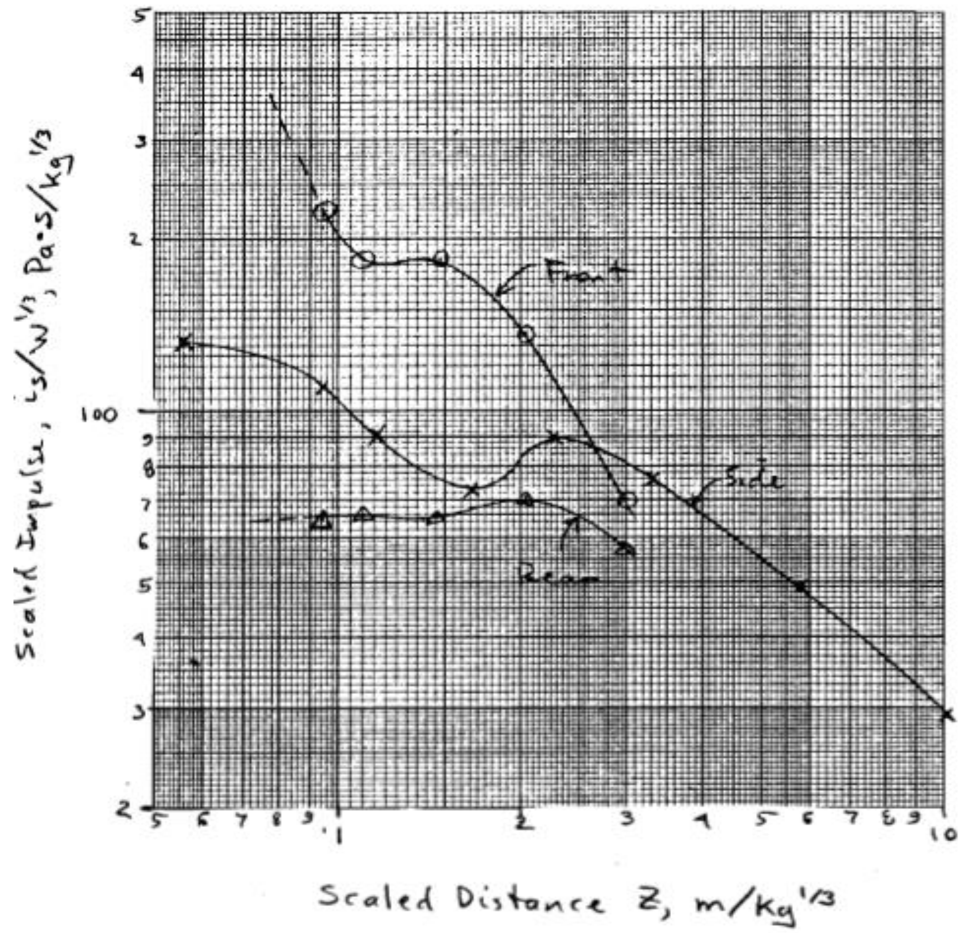



Fig. 2 Scaled Free-Field Blast Impulse,
Model Magazine Tests

We believe that the method and findings in this letter report are based on the most appropriate current technology for predicting the close-in blast loads which dominate in magazine design. Scaled quantities of explosive agree almost exactly with model-scale test data.

Estimates are made only for standard earth cover. Effect of earth cover could be estimated using scaled data from the key BRL report. We haven't done this, because the effect is minor, provided there is some earth cover.

If you have any questions, please call or write.

Sincerely,

Wilfred E. Baker

Dr. Wilfred E. Baker, P.E.
President

/tme


Fig. 2b - Blast impulse-Scaled Distance curves developed by Dr. Baker

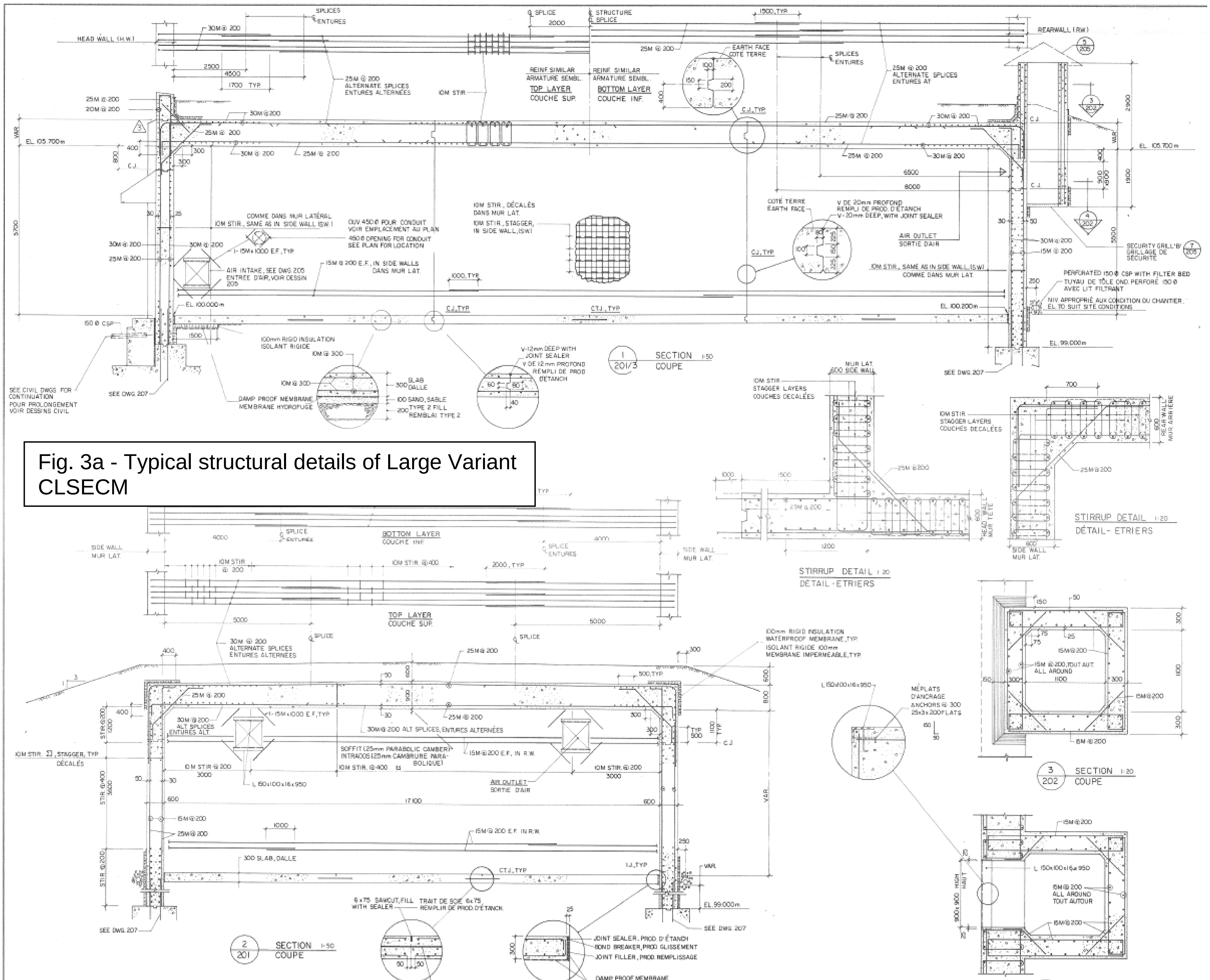



Fig. 3a - Typical structural details of Large Variant CLSECM

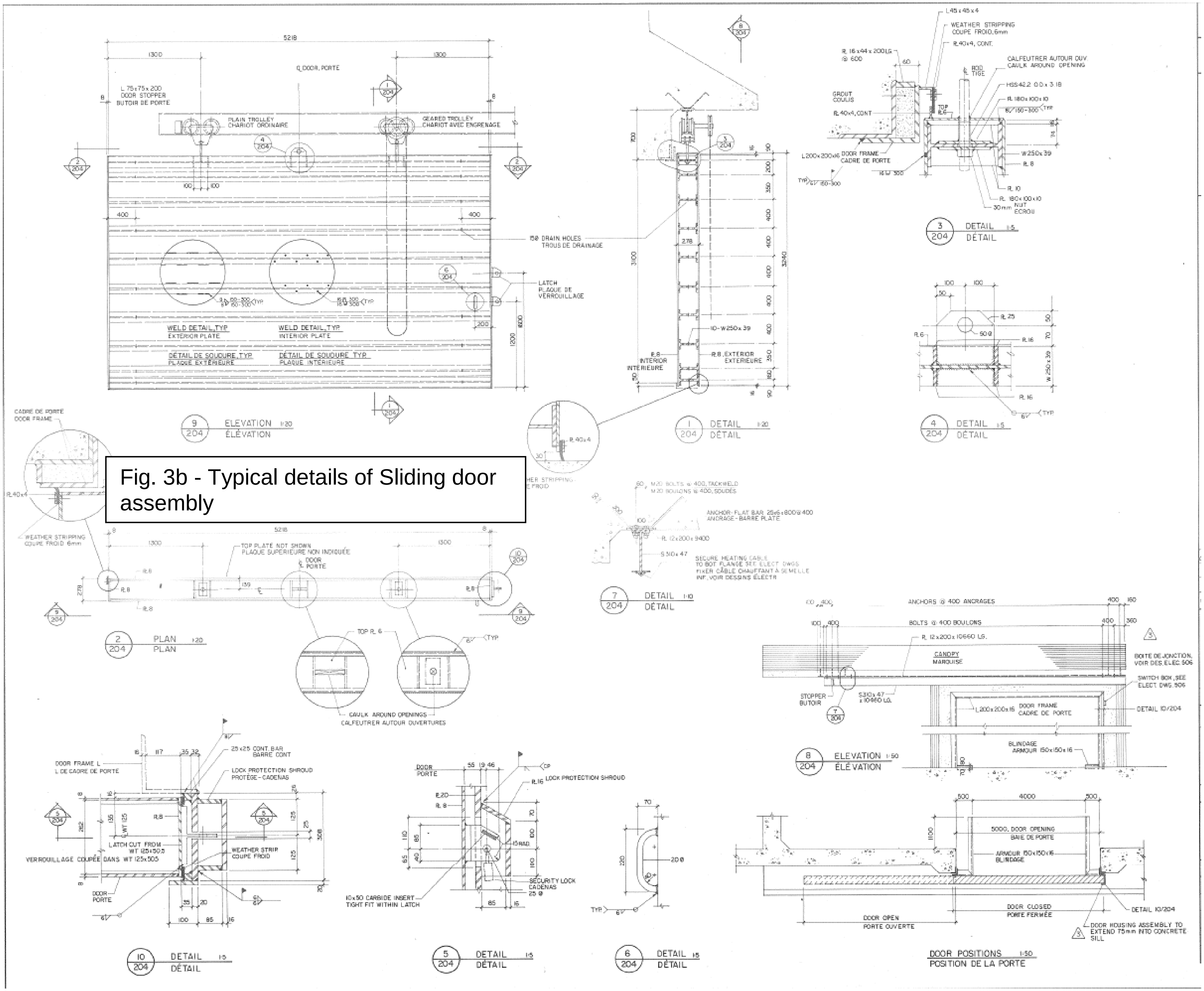


Fig. 3b - Typical details of Sliding door assembly

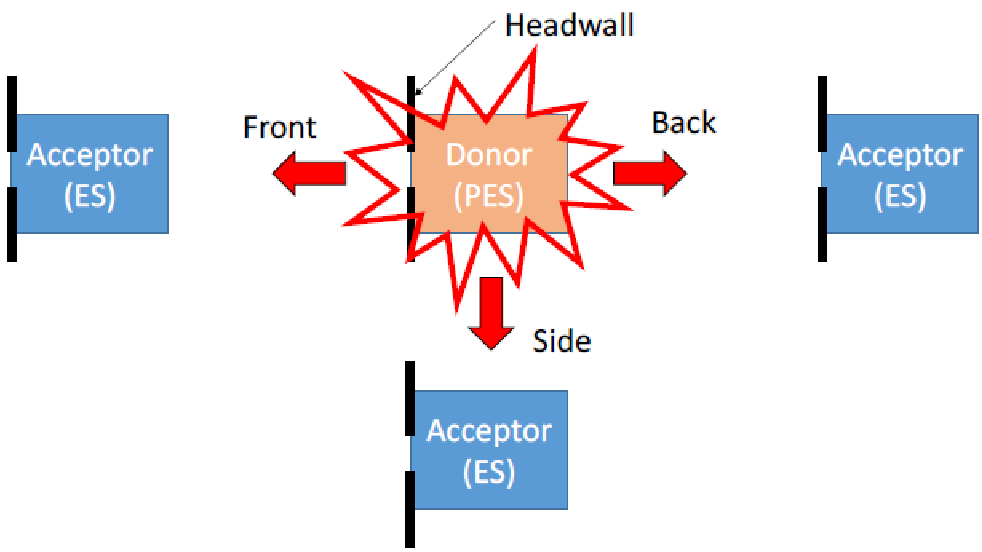



Fig. 4a - Possible locations of ES from PES for ECM blast design loading combinations

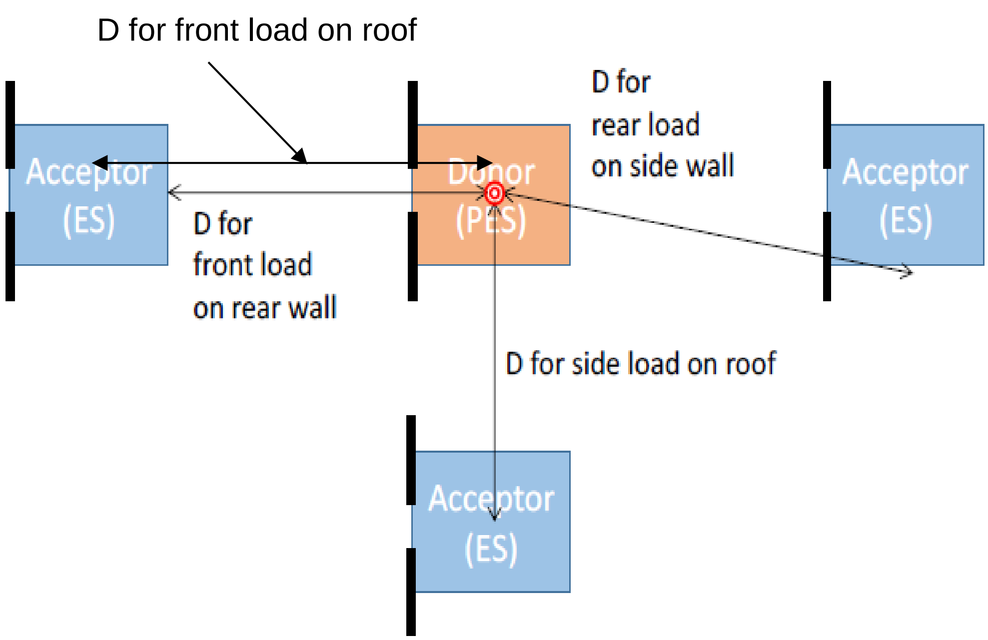



Fig. 4b - Stand-off distances from blast source (PES) to target components (ES) for estimating design blast loads
(D – Stand-off distances)

| Direction | Receptor (PES) ECM Type | US[1] | UK[2] | UN[3] | NATO[4] |
|---|---|---|---|---|---|
| Side-to-side | Undefined | 0.79 | 1.8 | 1.8 | 1.8 |
| | 3-bar | 0.5 | 0.5 | 0.5 | 0.5 |
| | 7-bar | 0.5 | 0.5 | 0.5 | 0.5 |
| Rear-to-front | Undefined | 2.38 | 2.4 | 2.4 | 2.4 |
| | 3-bar | 1.79 | 0.8 | 1.8 | 1.8 |
| | 7-bar | 0.79 | 0.8 | 0.8 | 0.8 |
| Front-to-rear | Undefined | 0.79 | 1.8 | 1.8 | 1.8 |
| | 3-bar | 0.79 | 0.8 | 0.8 | 0.8 |
| | 7-bar | 0.79 | 0.8 | 0.8 | 0.8 |

(1) DOD 6055.09-M, Table V3.E3.T6 (p. 37)
(2) JSP 482, Ed. 4, Table 1A (Ch 10, Sect 2, Annex A, p. 2)
(3) IATG 05.20, Ed. 2, (Annex D, Table D.2, p. 30)
(4) AASTP-1, Ed. B, Ver. 1, Table 1A (p. I-A-5)

Table 1 - Standard Inter-magazine scaled distances (metric) for ECMs (US,UK,UN,NATO)

| Series | Configuration | W [kg TNT] | V [m3] | W/V |
|---|---|---|---|---|
| BRL 2680 | Small W | 45,500 | 496 | 92 |
| | Medium W | 136,000 | 496 | 275 |
| | Large W | 227,000 | 496 | 458 |
| | | | | |
| CLSECM | Large variant | 250,000 | 2,740 | 91 |
| | Small variant | 45,000 | 1,730 | 26 |

Table 2 - Variation of Loading Density between Model test results and CLSECM

| Metric | Acceptor (ES) Component | Donor (PES) ECM Type | US[1] | UK[2] | UN[3] | NATO[4] |
|---|---|---|---|---|---|---|
| Pressure | Head wall | Undefined | — | — | — | — |
| | | 3-bar | 300 | 300 | 300 | — |
| | | 7-bar | 700 | 700 | 700 | ≥ 700* |
| | Roof | Undefined | 745 | — | — | — |
| | | 3-bar | 745 | 600 | 600 | — |
| | | 7-bar | 745 | 600 | 600 | — |
| | Side wall | Undefined | — | — | — | — |
| | | 3-bar | — | 300 | 300 | — |
| | | 7-bar | — | 300 | 300 | — |
| Impulse | Head wall | Undefined | — | — | — | — |
| | | 3-bar | 100 | 100 | 100 | — |
| | | 7-bar | 123 | 200 | 200 | 200* |
| | Roof | Undefined | 170 | — | — | — |
| | | 3-bar | 170 | 100 | 100 | — |
| | | 7-bar | 170 | 100 | 100 | — |
| | Side wall | Undefined | — | — | — | — |
| | | 3-bar | — | 100 | 100 | — |
| | | 7-bar | — | 100 | 100 | — |

(1) DOD 6055.09-M, V2.E5.5.2.4 (p. 26)
(2) JSP 482, Ed. 4, §1.2 (Chap 6, Annex A, p. 2)
(3) IATG 05.20, Ed. 2 (Annex C, §C.1.1, p. 28)
(4) AASTP-1, Ed. B, Ver. 1, §2.3.2.2.2 (p. II-3-4)

Table 3 - Recommended blast loads on ECMs for Standard Inter-Magazine scaled distances (*Note the variation in loads between various publications*)

| Metric | Component | QD Standards for 7-bar ECM | |
|---|---|---|---|
| | | Value | Source |
| Pressure [kPa] | Head wall | 700 | All* |
| | Roof | 745 | US |
| | Side wall | 300 | UK/UN |
| Impulse [kPa-ms/kg$^{1/3}$] | Head wall | 200 | All** |
| | Roof | 170 | US |
| | Side wall | 100 | UK/UN |

(*) NATO requires ≥ 700 and is limited to NEQ ≤ 75,000 kg

(**) NATO requires ≥ 200 and is limited to NEQ ≤ 75,000 kg

Table 4 - Worst possible load scenario for 7 bar ECM blast loads

| Metric | Component | QD Standards for 3-bar ECM | |
|---|---|---|---|
| | | Value | Source |
| Pressure [kPa] | Head wall | 300 | US/UK/UN |
| | Roof | 745 | US |
| | Side wall | 300 | UK/UN |
| Impulse [kPa-ms/kg$^{1/3}$] | Head wall | 100 | US/UK/UN |
| | Roof | 170 | US |
| | Side wall | 100 | UK/UN |

Table 5 - Worst possible load scenario for 3 bar ECM blast loads

Table 6 - Blast loads & Response of ECM components for various Load cases

| Load Case | Pressure (kPa) | Impulse (kPa-ms) | Peak deflection (mm) | Rotation {deg) |
|---|---|---|---|---|
| Design (front-rear) | 550 | 9,625 | 238 | 1.6 |
| Design verification (front-rear) | 448 | 11,407 | 274 | 1.8 |
| Design verification (side-side) | 368 | 6,931 | 148 | 1.0 |
| 7 bar load | 745 | 10,709 | 308 | 2.1 |

**ROOF**

| Load Case | Pressure (kPa) | Impulse (kPa-ms) | Peak deflection (mm) | Rotation {deg) |
|---|---|---|---|---|
| Design (rear-front) | 420 | 7,980 | 14.4 | 0.29 |
| Design verification (rear-front) | 417 | 12,510 | 10.1 | 0.20 |
| Design (side-side) | 275 | 11,825 | 9.2 | 0.18 |
| Design verification (side-side) | 369 | 6,971 | 10.3 | 0.21 |
| 7 bar load | 700 | 12,600 | 30.6 | 0.60 |
| 3 bar load | 300 | 6,300 | 9.2 | 0.18 |

**HEADWALL**

| Load Case | Pressure (kPa) | Impulse (kPa-ms) | Peak deflection (mm) | Rotation {deg) |
|---|---|---|---|---|
| Design (rear-front) | 420 | 7,980 | 223 | 5.1 |
| Design verification (rear-front) | 417 | 12,510 | 172 | 3.9 |
| Design (side-side) | 275 | 11,825 | 147 | 3.4 |
| Design verification (side-side) | 369 | 6,971 | 179 | 4.1 |
| 7 bar load | 700 | 12,600 | Failure | Failure |
| 3 bar load | 300 | 6,300 | 137 | 3.1 |

**DOOR (**Door fails in shear under 7 bar load)

NOTE: Design refers to Original design completed in late 80s
Design verification refers to recent design verification completed in 2016

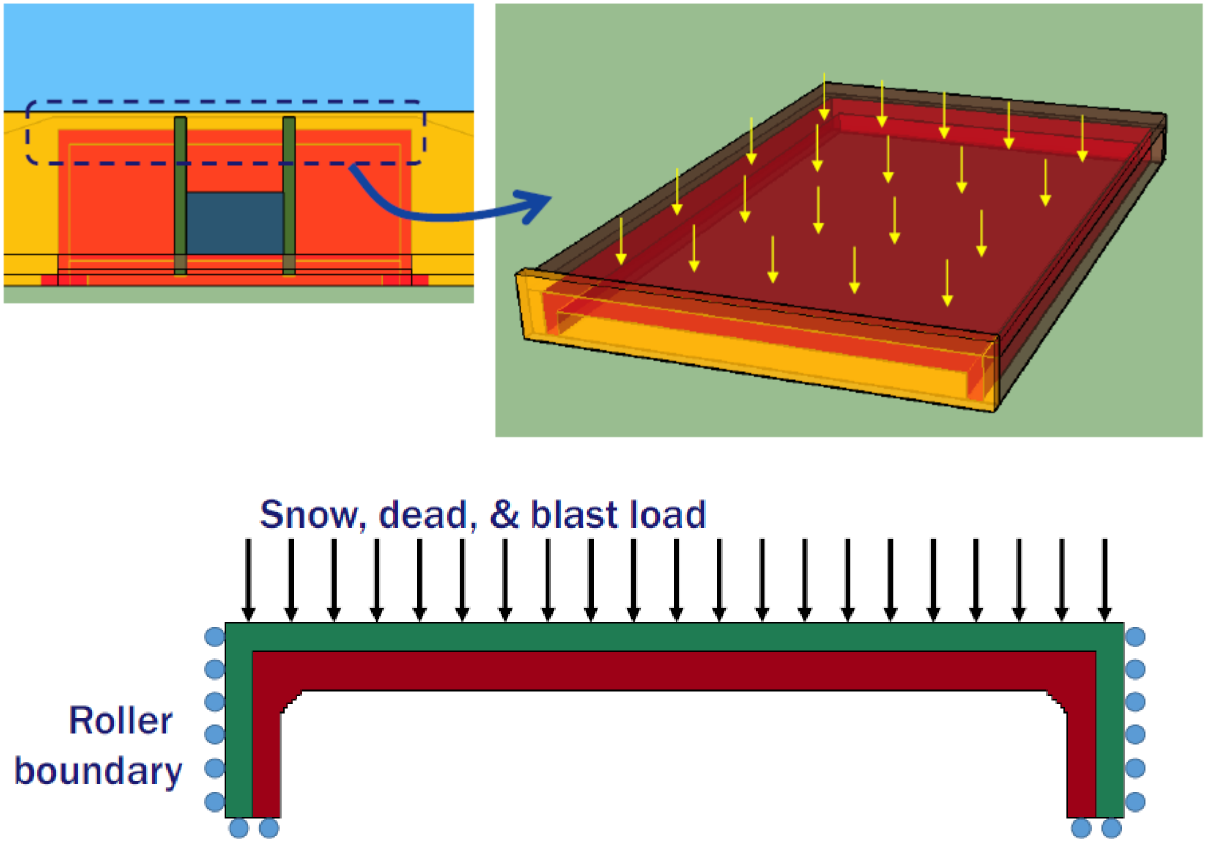



Fig. 5a - FEM integrated model for the design/analysis of roof component using LS-DYNA software (*shows elevation, cross section and plan views*)

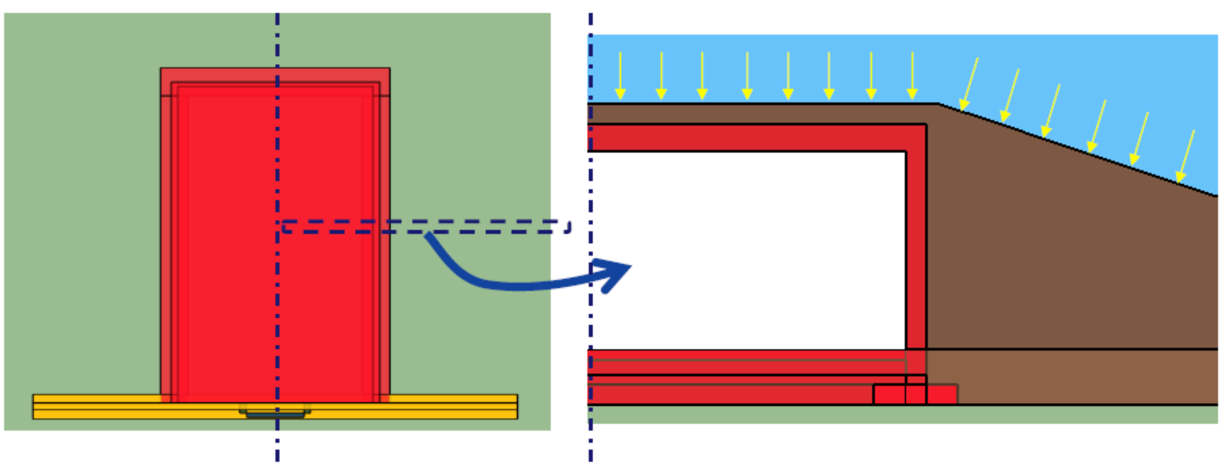


Fig. 5b - FEM 2D slice model used to analyze side wall response

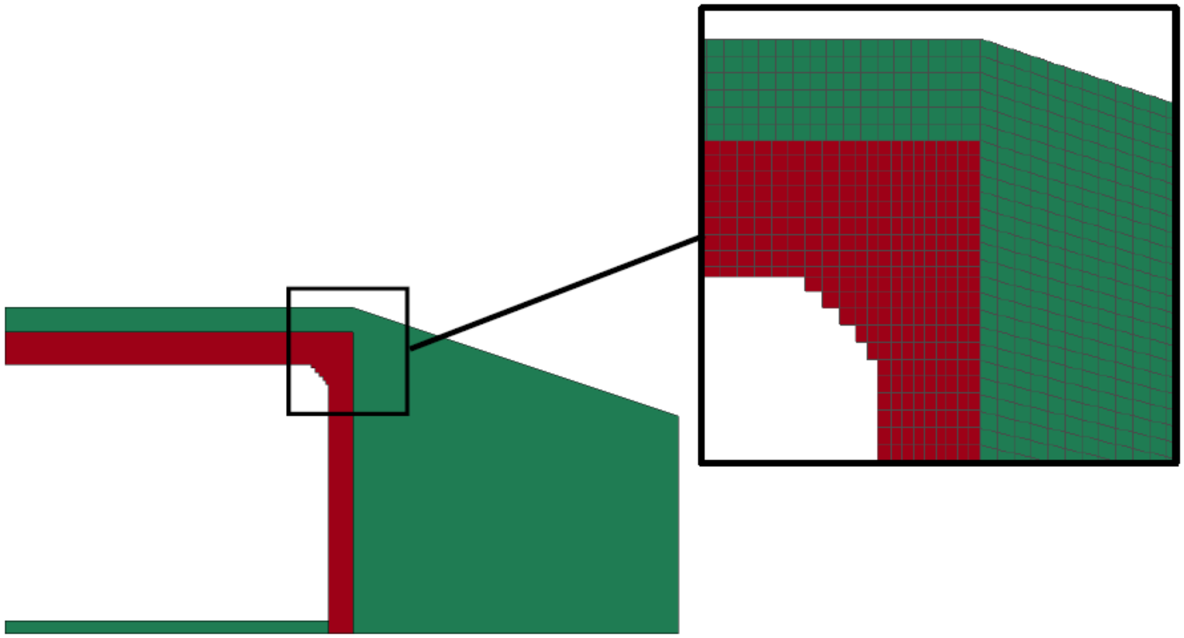


Fig. 5c - Shows details of meshing for concrete and surrounding soil mass

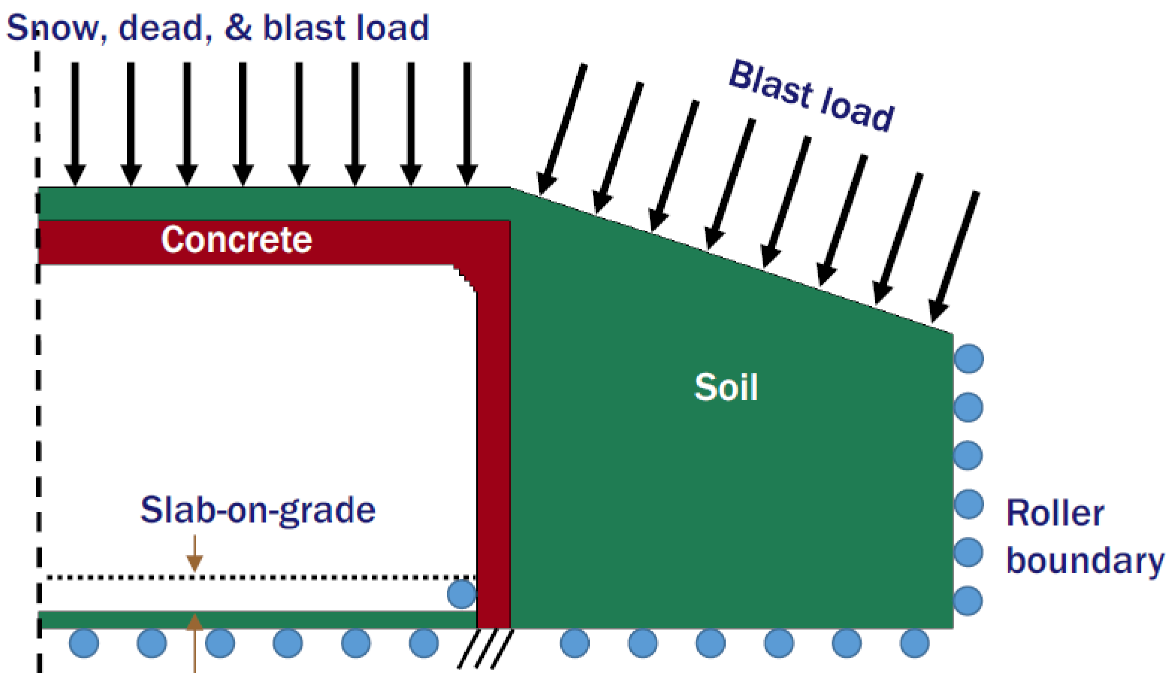



Fig. 5d - Shows application of both conventional and blast loads on CLSECM

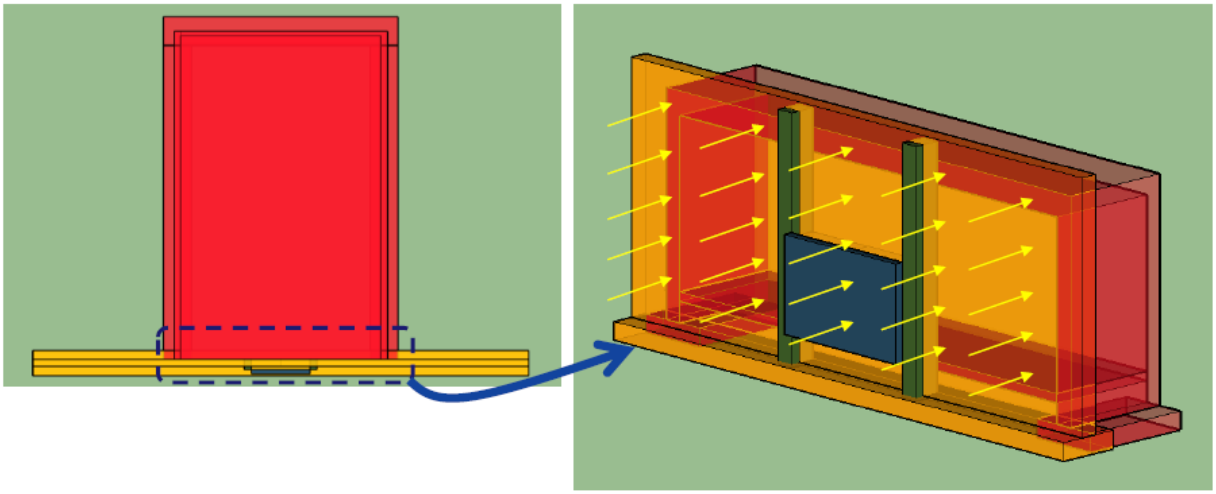


Fig. 6a - FEM model simulation for the front headwall-door system

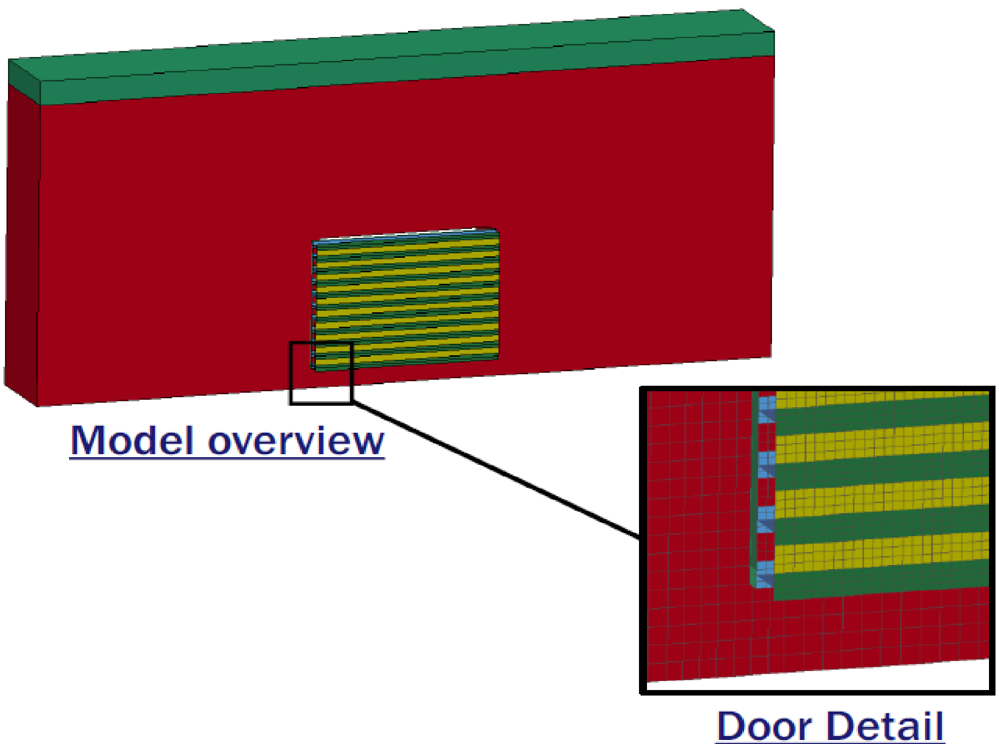



Fig. 6b - FEM model simulation of sliding door

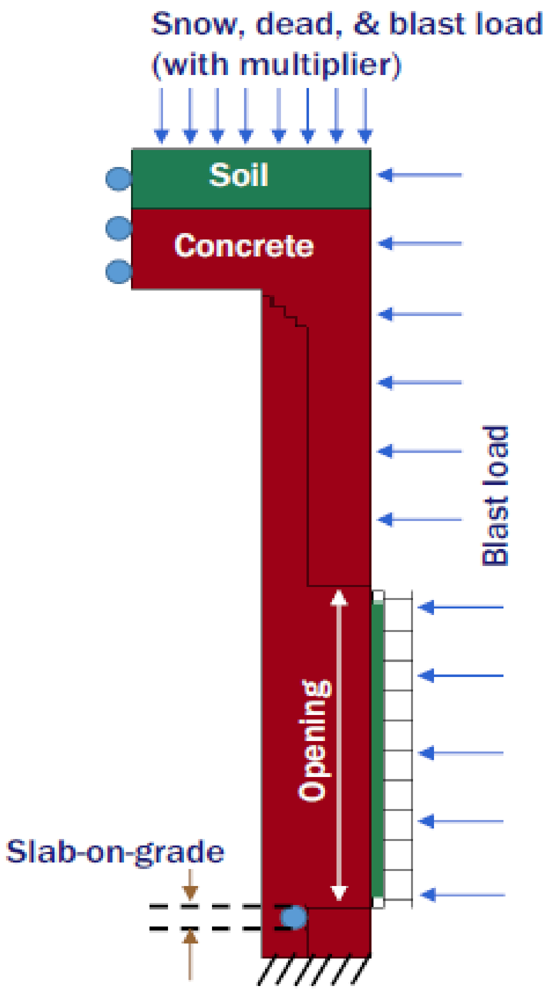
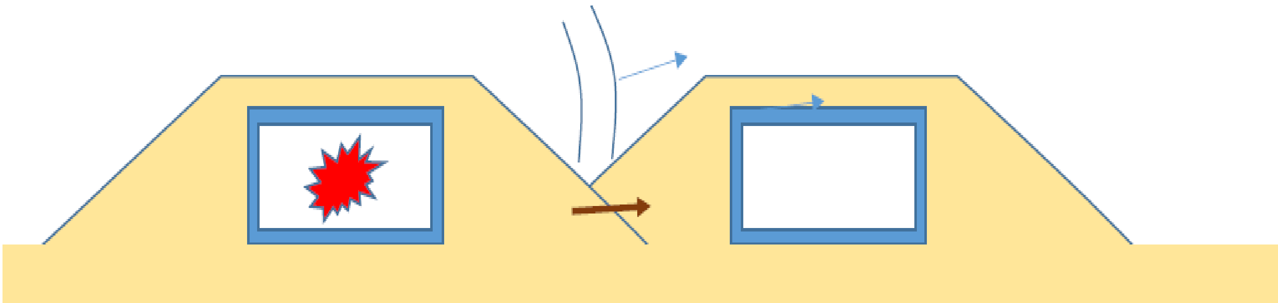
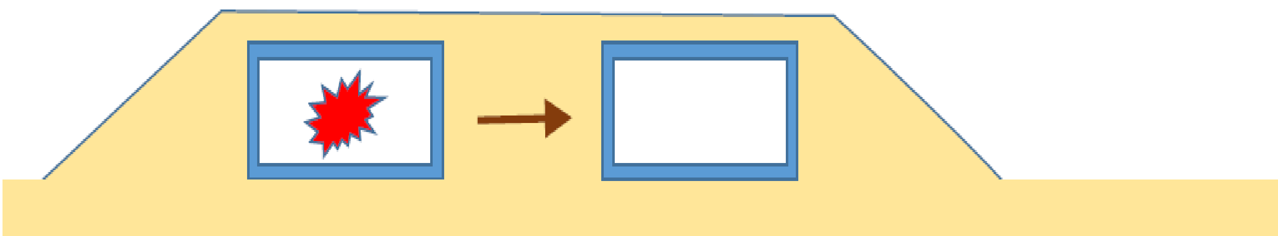



Fig. 6c - Cross Section of FEM Model for the front head wall/door system for design/analysis



(b) ECMs with partially overlapping berms.



(c) ECMs with fully overlapping berms.

Fig 7 – Effect of earth fill overlap on the integrity and storage capacity of CLSECM as an ES

Fig 8a – Push through of door due to shear failure for 7 bar load (before retrofit)

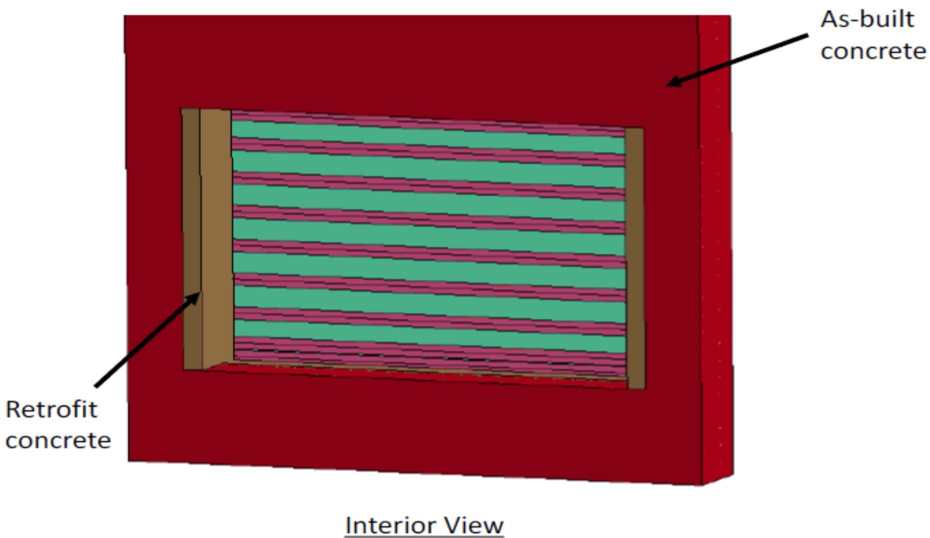



Fig 8b - Interior view of the added retrofit precast block attached to the pilasters at either end

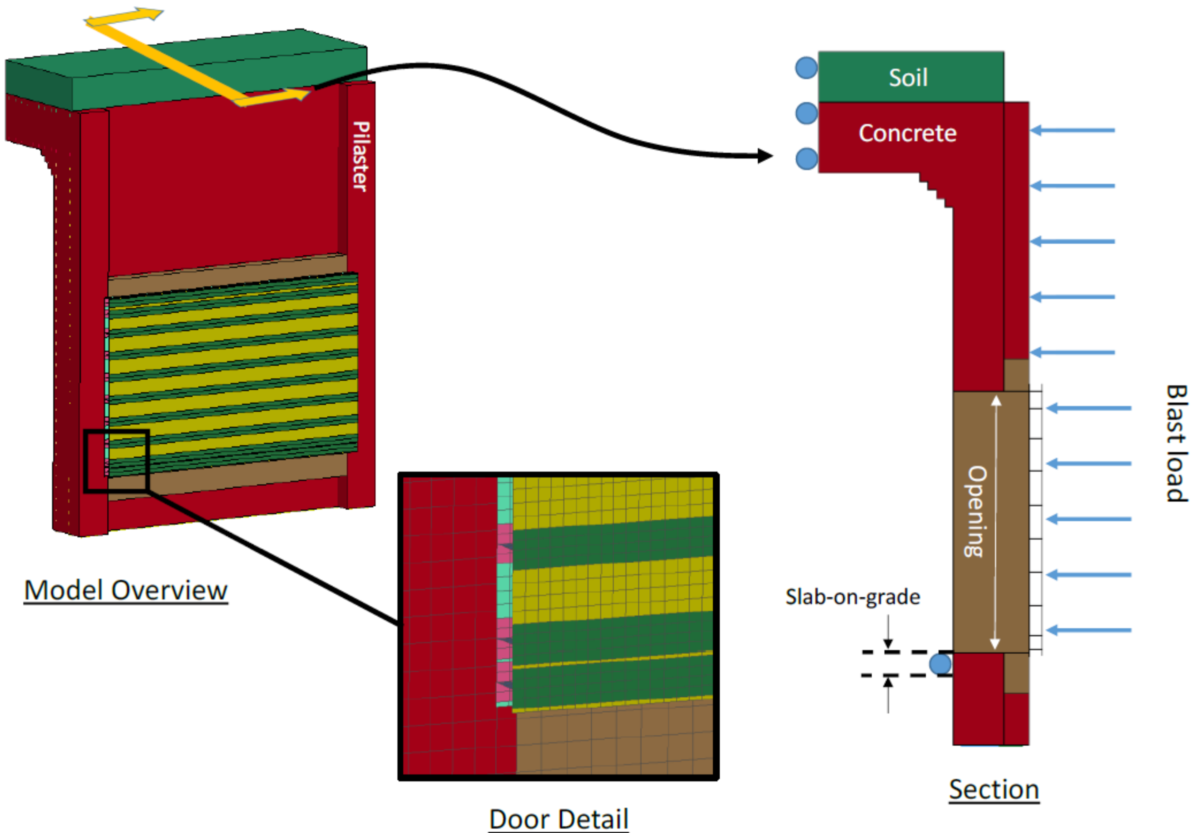



Fig 8c - Headwall and Door model for analysis

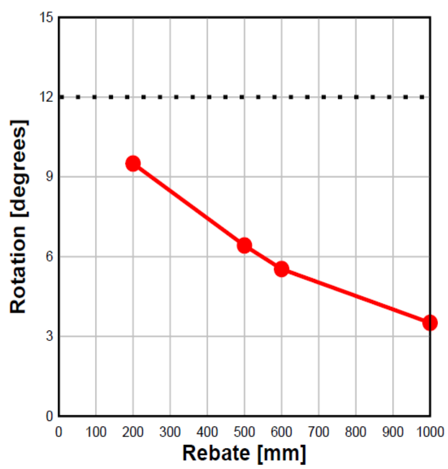



Fig 9a - Rotation at door end for various thickness of precast blocks added to the pilaster

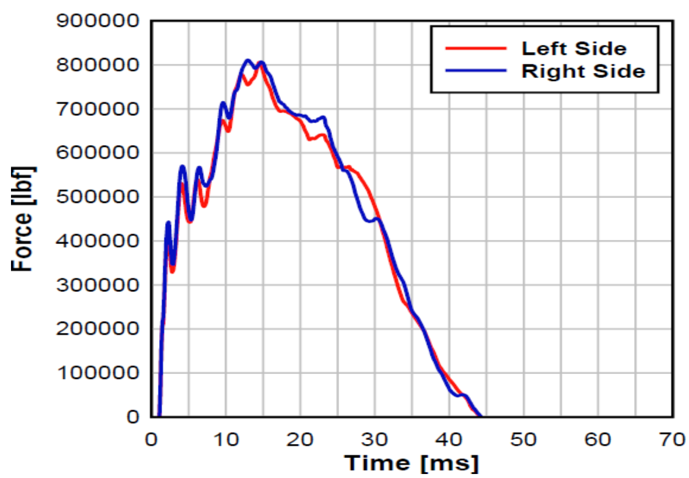
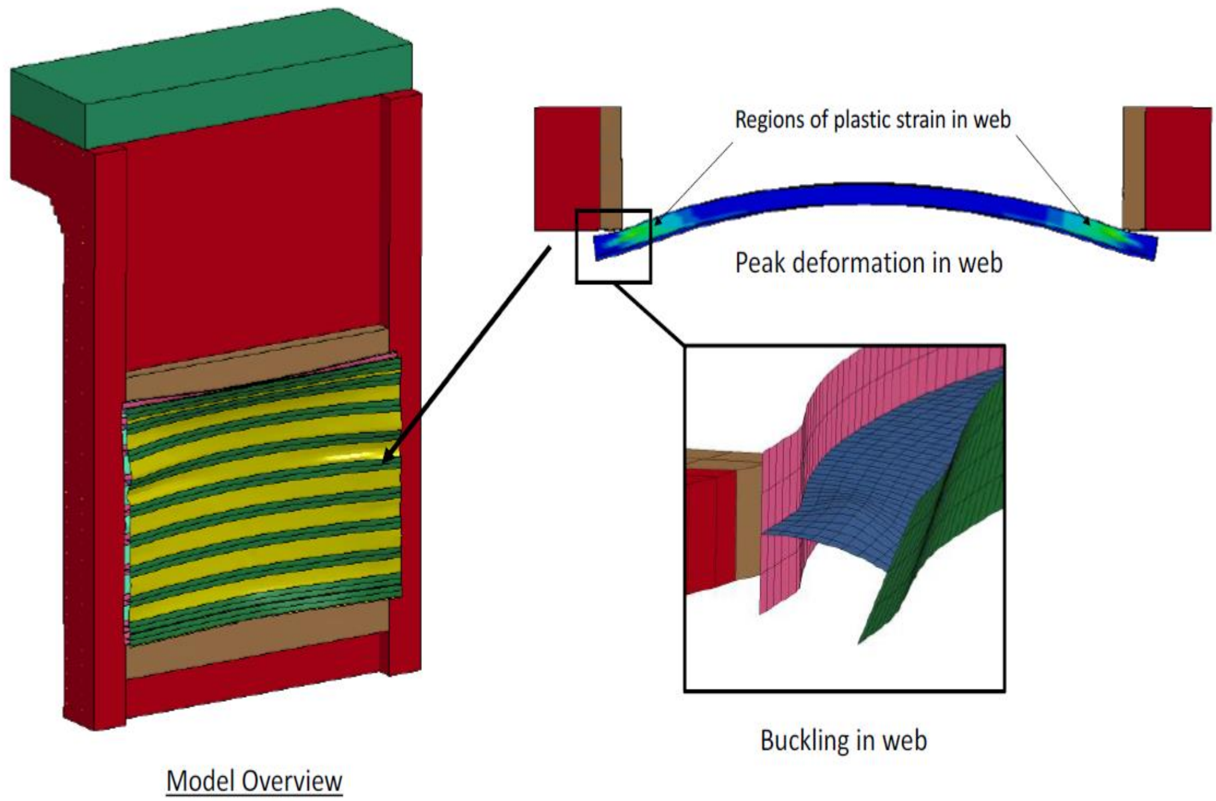
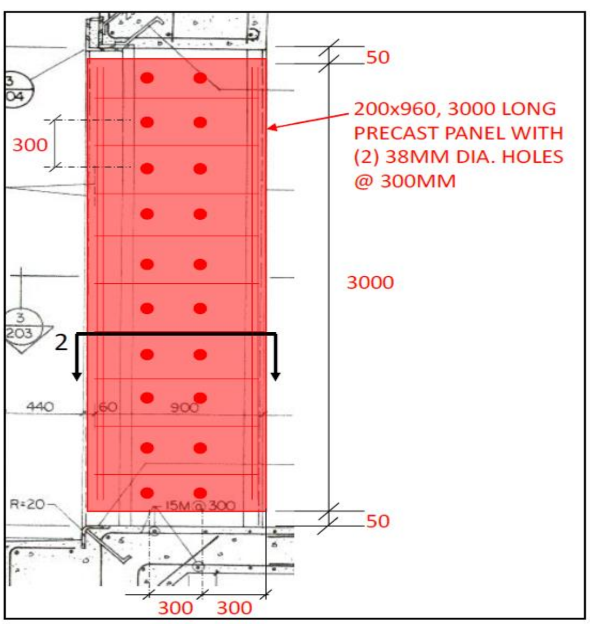
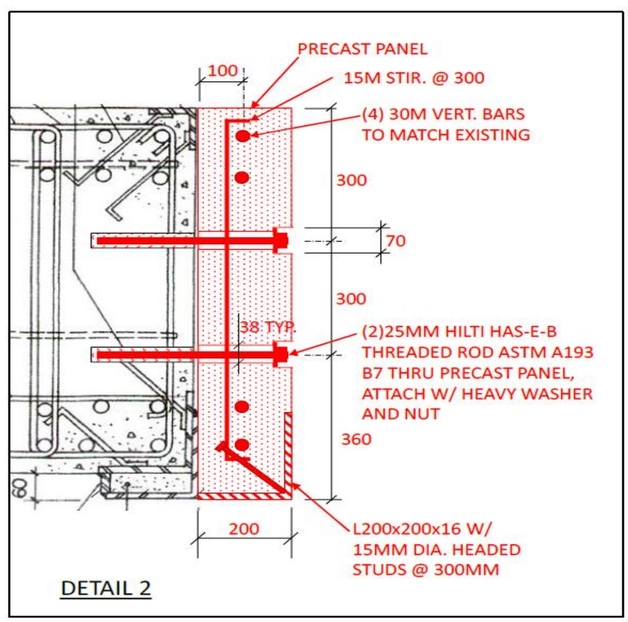



Fig 9b - Reaction force to be resisted by precast block




Elevation view of Precast block




Plan view of Precast block

Fig 10 - Door response for 7 bar load with 200 mm precast blocks added to reduce door opening – no inward movement of door despite yielding of web (after retrofit)

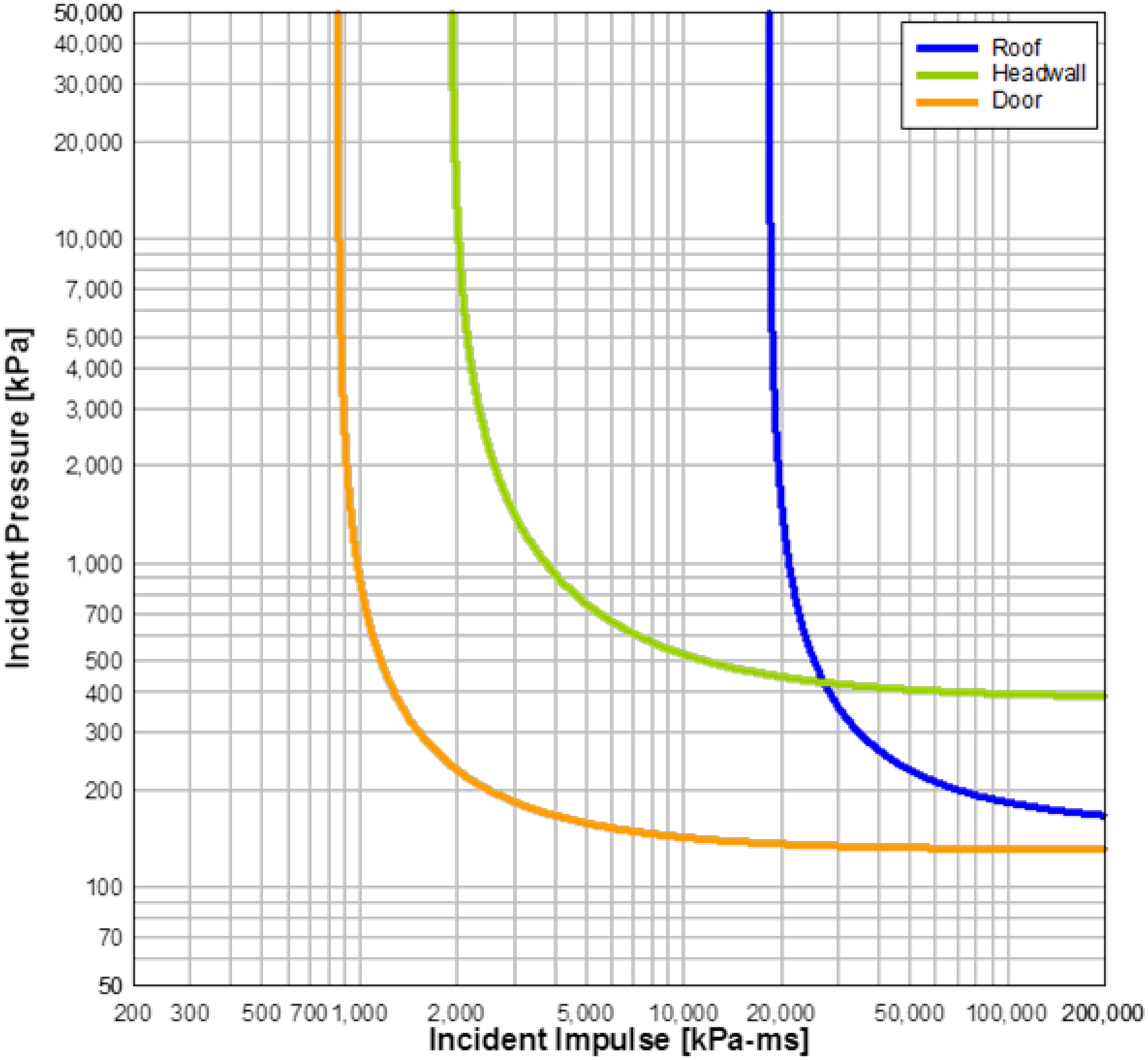



Fig 11 - Typical PI diagram response for the Large variant CLSECM components

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