National Defence Défense nationale

ASSISTANT DEPUTY MINISTER (INFRASTRUCTURE AND ENVIRONMENT)

PLACE L2 HERE (DG LEVEL)

Canadian Long Span Earth Covered Magazine (CLSECM)

Design Challenges

2018 – International Explosives Safety Symposium & Exhibition

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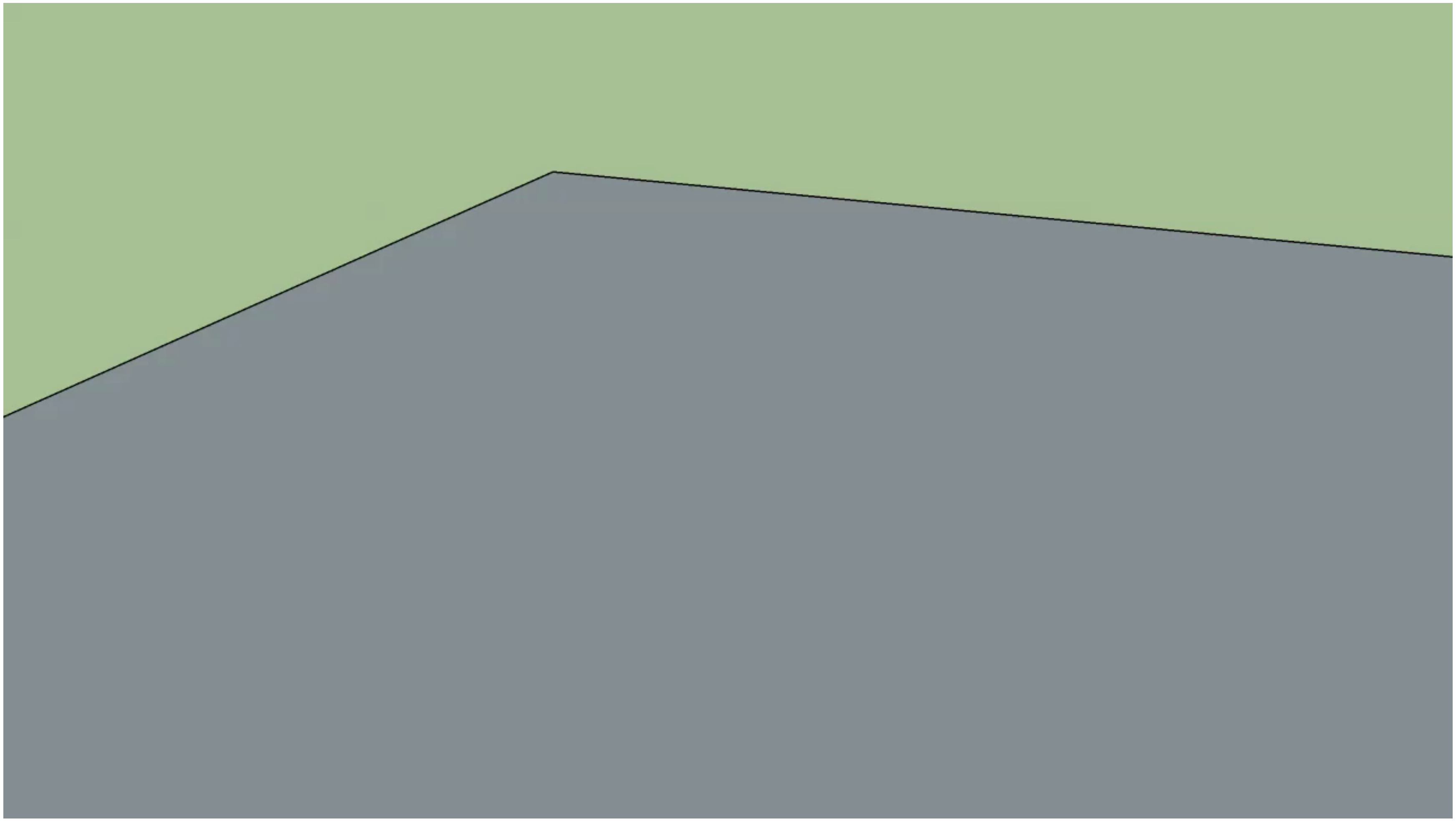
Outline of presentation

- Unique features/requirements of CLSECM
- Design issues/challenges
  - Original design (early 1990s)
  - Design verification (2016/17)
  - ECM Bar-Rating classification
- Remedial action for design inadequacy
- Impact of earth fill overlap between ECMs
- Conclusions

CLSECM structure requirements

- Column free large clear span for easy warehousing
- Retain clear span but accept minimal change to other structural dimensions to accommodate varying quantities of ammunition and explosives
- Large door opening to permit entry/exit of Flat-Bed trucks loaded with ammunition pallets + Fork Lift Trucks
- Electrical/Mechanical Annex separate from storage area

CLSECM Anatomy



CLSECM – Design features

- Two types were developed in early 1990s by department engineers
  - Large variant (17.1m wide x 28.75m long x 5.7m high) *houses 250,000 kg of Equiv. TNT of HD 1.1*
  - Small variant (17.1m wide x 18m long x 4.2m high) *houses 40,000 kg of Equiv. TNT of HD 1.1*
- Design standard – AC 258, predecessor to the current AASTP – 1, NATO document on Explosives Safety Storage and Operations
- AC 258 required design of ECM to 7 bar (103 psi) blast load on roof and head wall/door assembly at separation scaled distance (m) of *a) side-side at 0.5 Q 1/3 and b) front/rear or rear/front at 0.8 Q 1/3, where Q is the maximum Net Explosives Quantity (NEQ) in kg.*

CLSECM – Design features (Cont'd)

- Resistant to 7 bar blast load on the large span roof of CLSECM did not seem efficient and cost-effective; hence, idea was to increase separation distances to reduce the blast load on the roof.
- No standard or guidance was available for determination of blast loads on varying Inter-Magazine-Distance (IMD) between ECMs.
- Late Dr. Wifred Baker, well known US Blast Physicist, assisted in the determination of ECM blast loads from varying IMDs, based on the data available from ESKIMO field and Lab tests – BRL 2680 steel arch ECMs. Developed Pressure/Impulse and Scaled distance curves.

ECM Blast Loads

Pressure

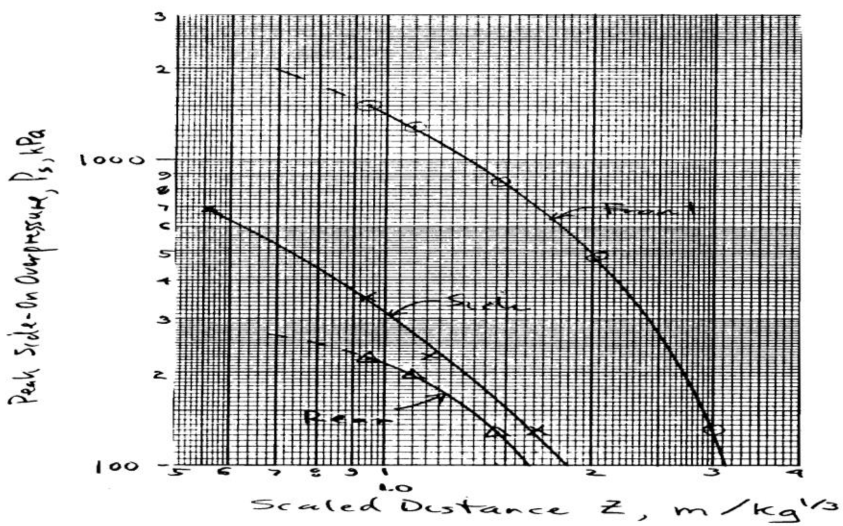


Fig. 1 Free-Field Blast Overpressure, Model Magazine Tests

Impulse

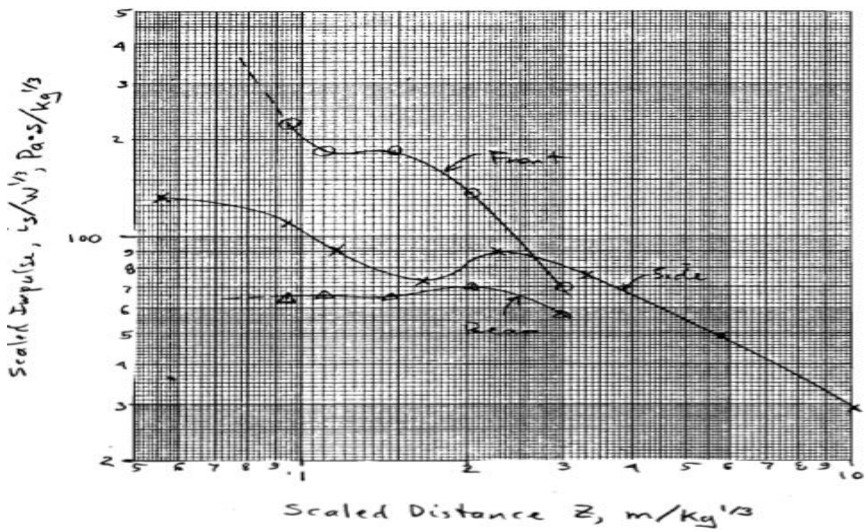
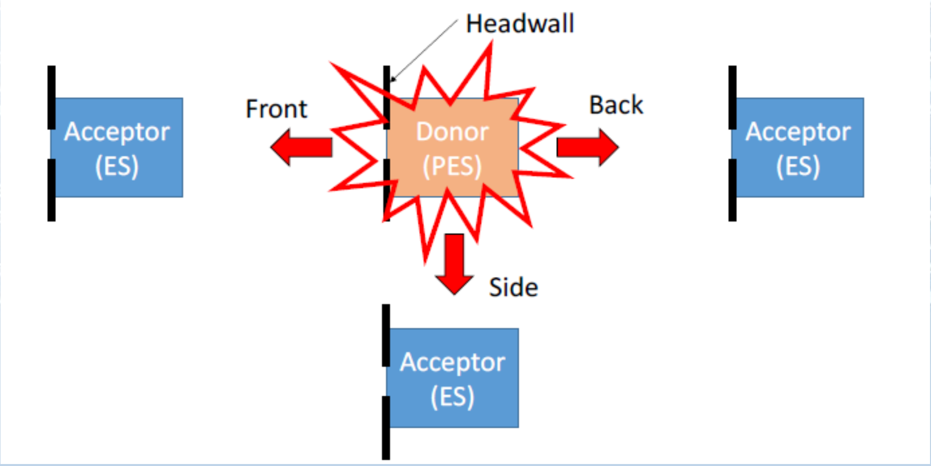


Fig. 2 Scaled Free-Field Blast Impulse, Model Magazine Tests

CLSECM – Separation Scaled Distance (m)

	Small variant	Large variant	7-bar ECM standard
Side-to-side	$0.6\ Q^{1/3}$	$0.6\ Q^{1/3}$	$0.5\ Q^{1/3}$
Rear-to-front	$1.1\ Q^{1/3}$	$1.4\ Q^{1/3}$	$0.8\ Q^{1/3}$
Q	40-45,000 kg	250,000 kg	—



CLSECM – Analysis/ Design

Large Variant CLSECM (max.loads)

Roof – 5.5 bar & 35 msec (Incident pressure)
Head wall/Door assembly – 4.2 bar & 38 msec (Reflected pressure)

Dynamic Design using SDOF analysis using decoupled components and component response, based on TM 5-1300, predecessor to UFC 3-340-02

Small Variant

Large Variant

Interior View

CLSECM design verification in 2016/17- Why

- Original design was completed in early 1990s
- Possible advancements in ECM design procedures, blast evaluation methods, and sophisticated analytical tools
- Lack of Bar Rating classification - required for licensing purposes of ECMs, based on QD criteria.

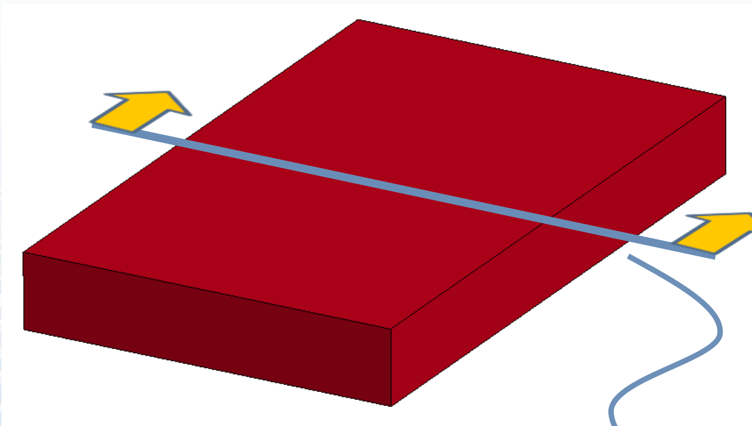
CLSECM design verification – Loads/Analysis

- Conduct state-of the art literature study on ECM design and select the most appropriate procedure; consulted standards/publications on ECMs from US, UK, UN, NATO, Canada
- Self-weight of soil and concrete
  - Accounted for in FE model (LS-DYNA) by applying global acceleration to entire model
- Snow loads 3.2 kpa
- Dynamic Blast loads determined using BEC 7.0 tool

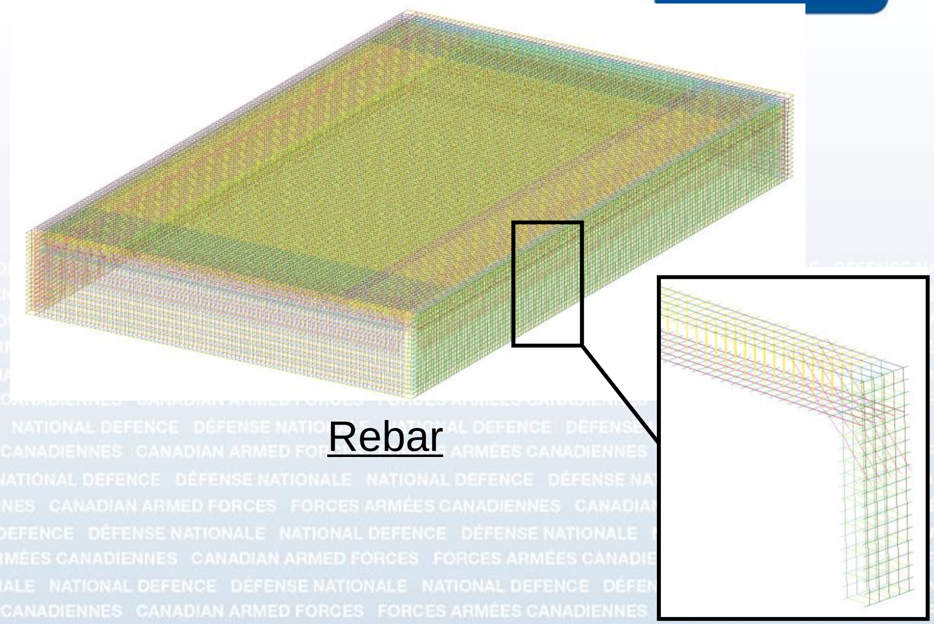
  (Studied adjustments to blast loads due to the impact of CLSECM features (Explosives density Q/V ratio, flat RC roof versus arched roof, thicker concrete skin etc.) on the data set used in the derivation of BEC curve fit; no adjustments were finally considered to be of significance)
- Non Linear dynamic analysis using LS-DYNA software and component design verification using UFC 3-340-02-Protection Category Level 3.
- Response criteria; Roof & Walls < 6 deg; Steel door < 12 deg, allowing for clearances for the stacked ammunition pallets to prevent impact from deforming components

For more details on the design verification, refer to Report on Structural response evaluation of CLSECMs, March 2017, Baker Engineering and Risk Consultants Inc.,California, USA

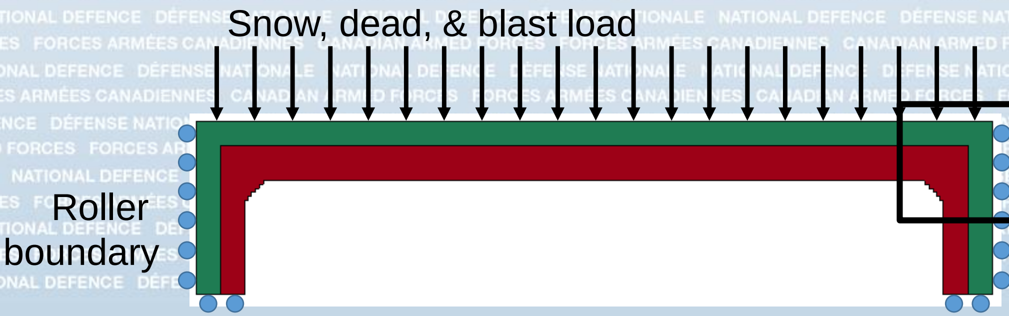
FE model - Roof



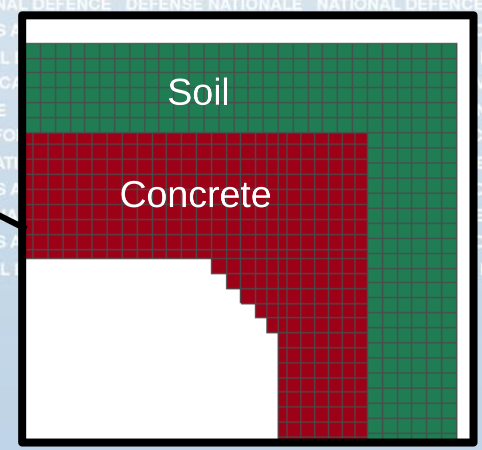
Model overview



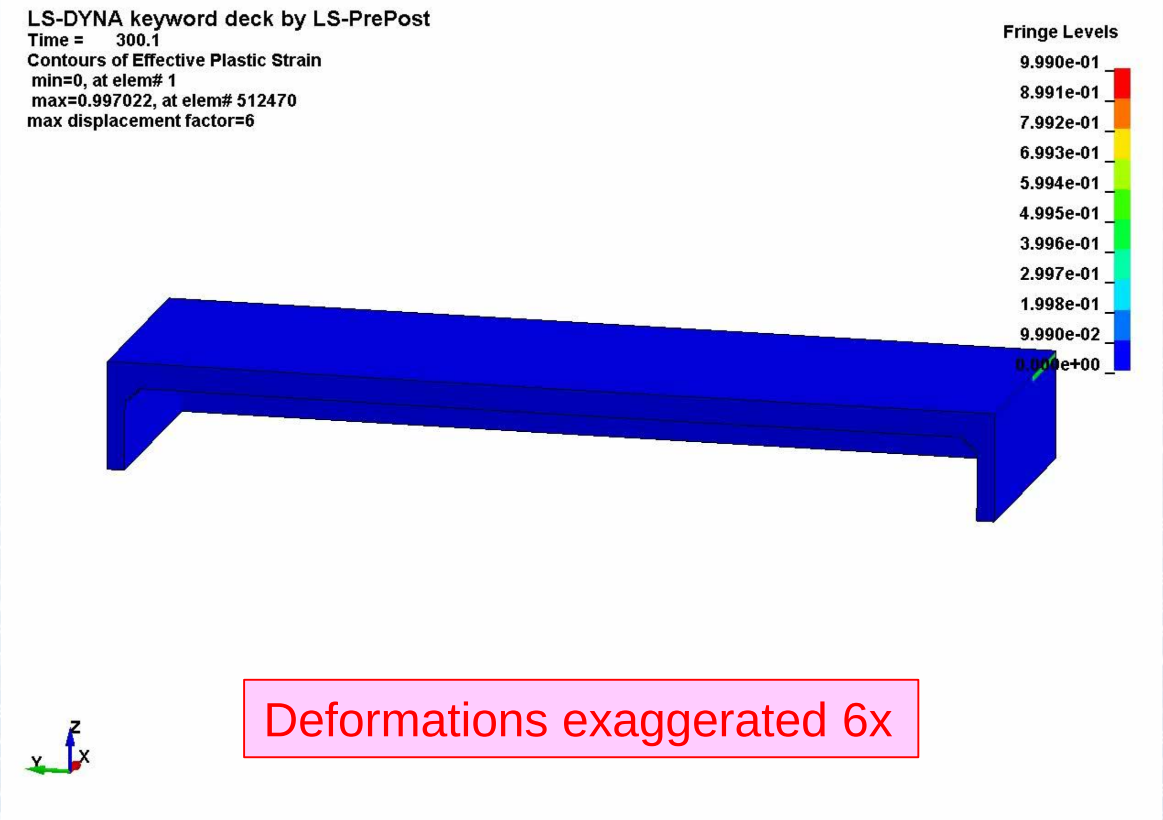
Rebar

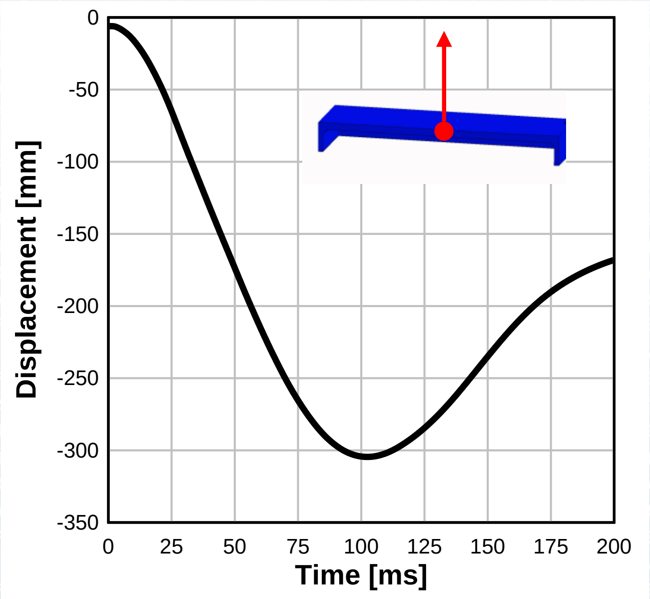


Cross-section



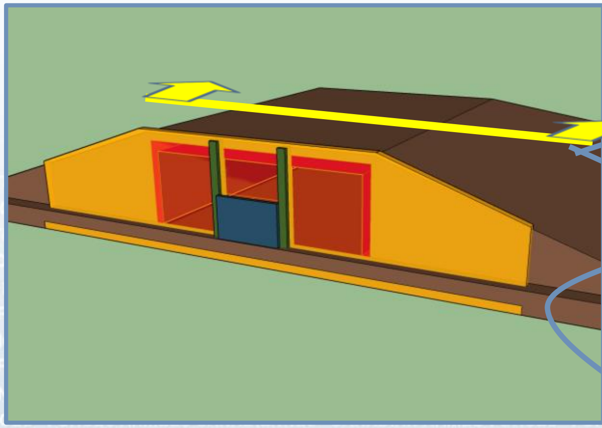
Roof dynamic response

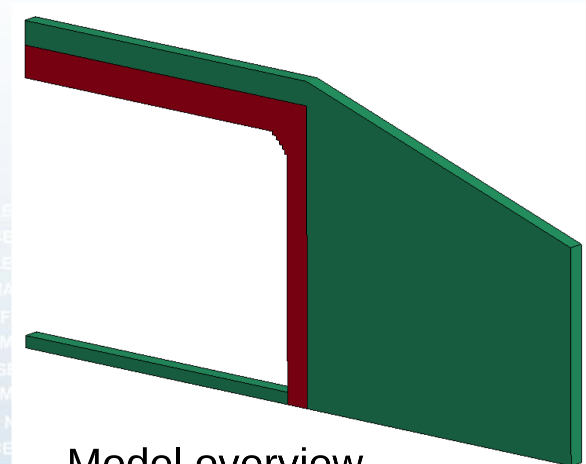




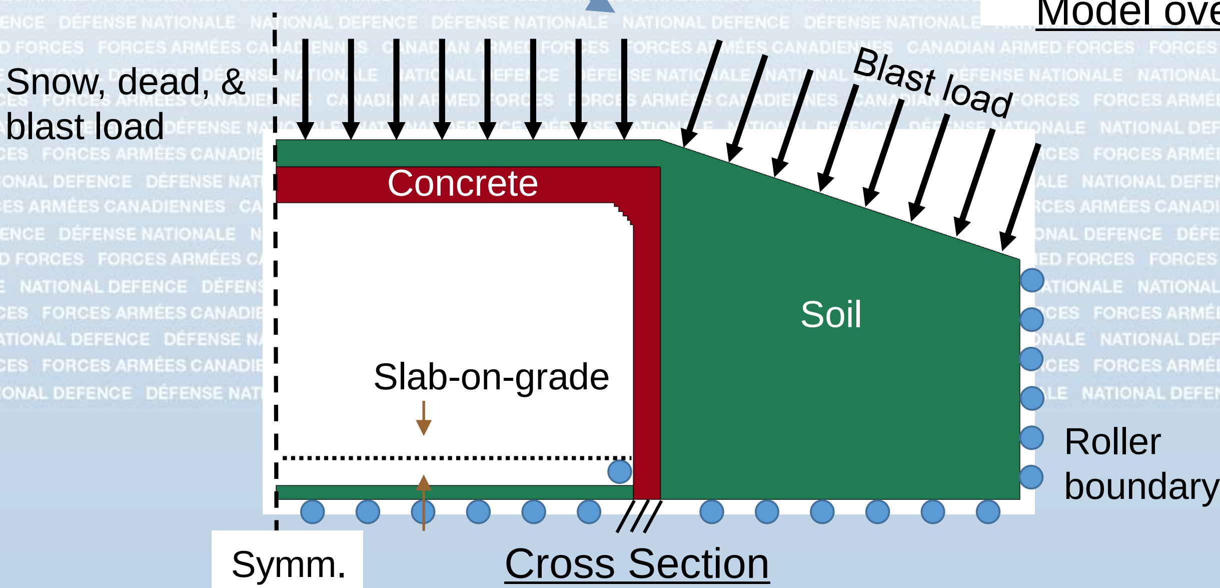
Load: 7-bar QD, p = 745 kPa, I = 170 kPa-ms/kg$^{1/3}$

FE model - Sidewall

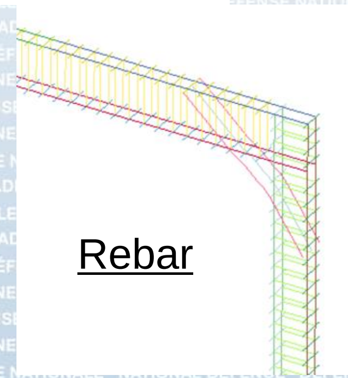




Model overview

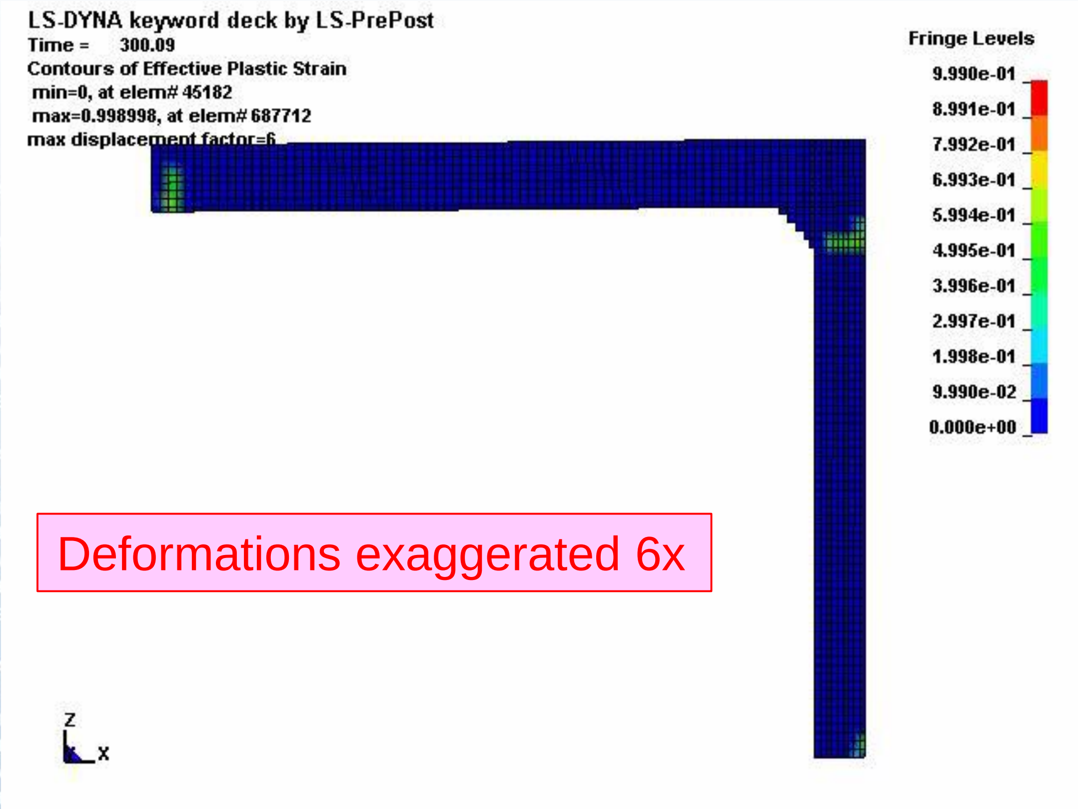


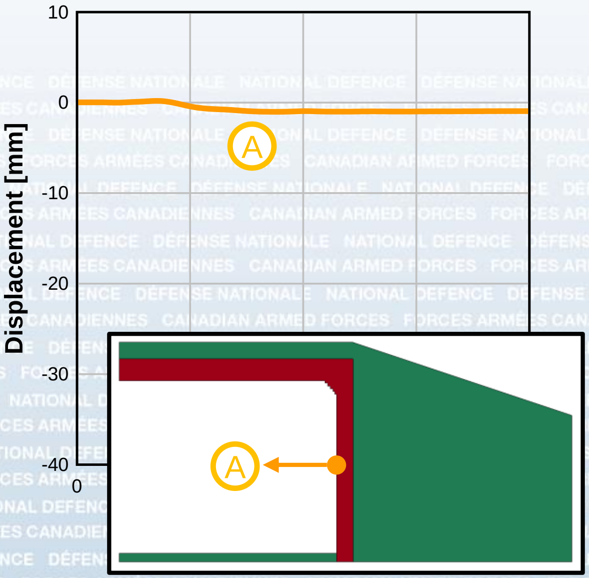
Cross Section



Rebar

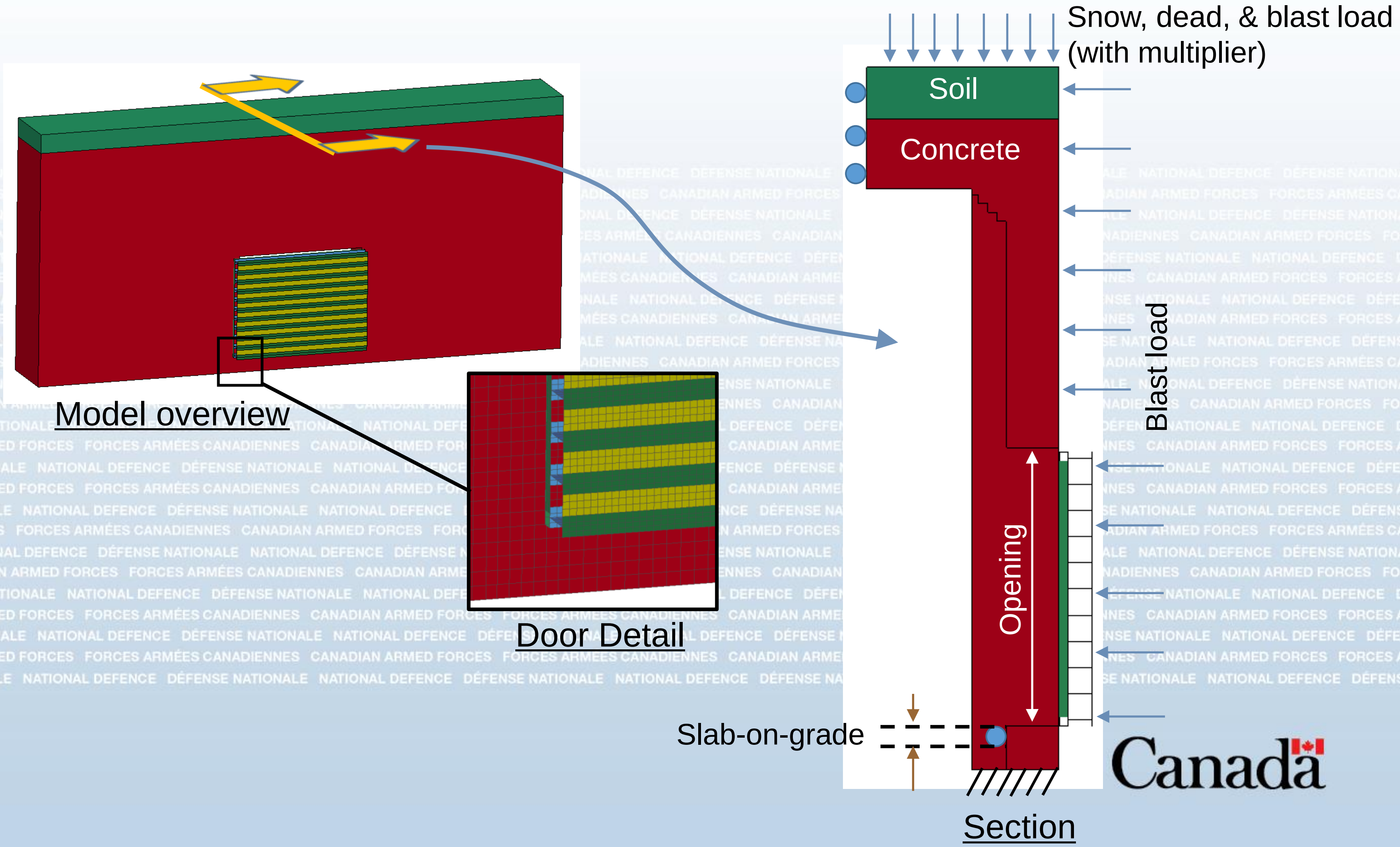
Sidewall Response



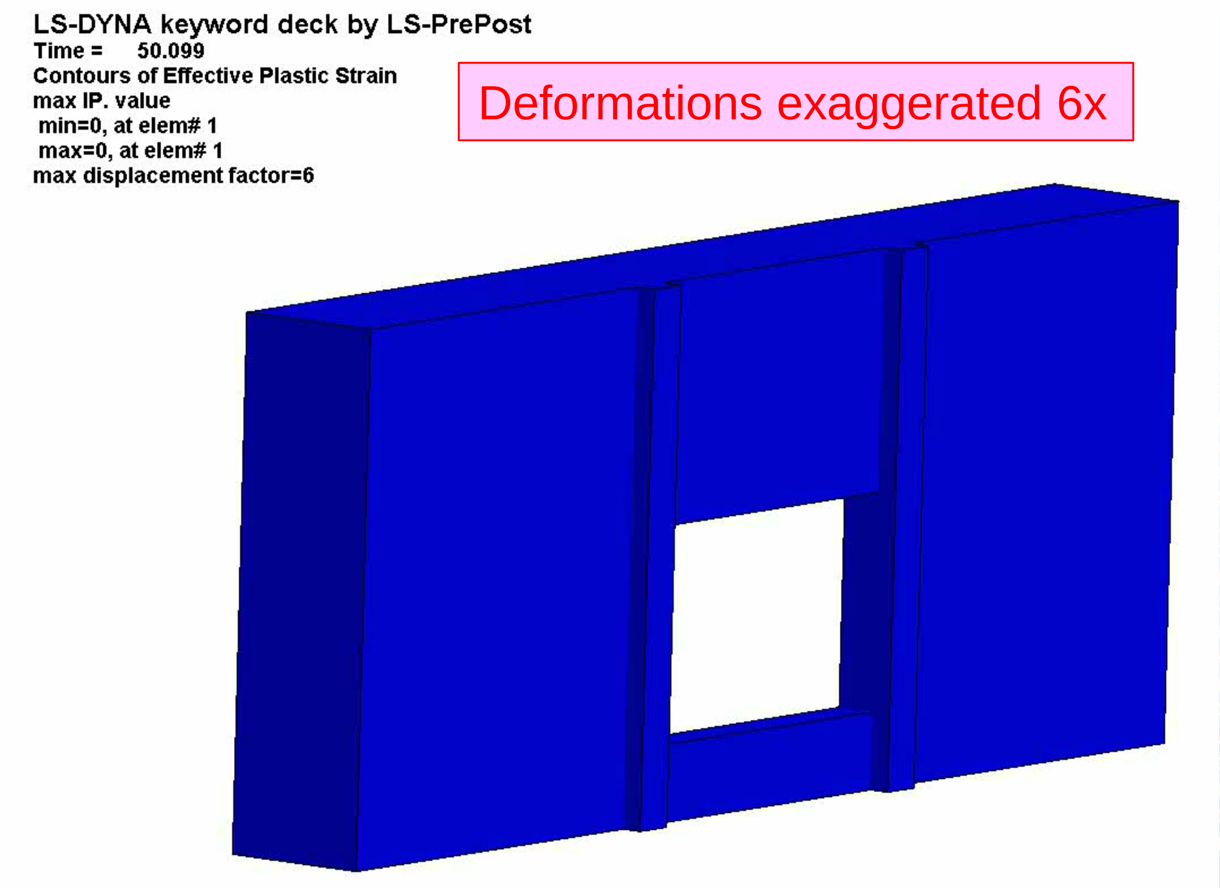


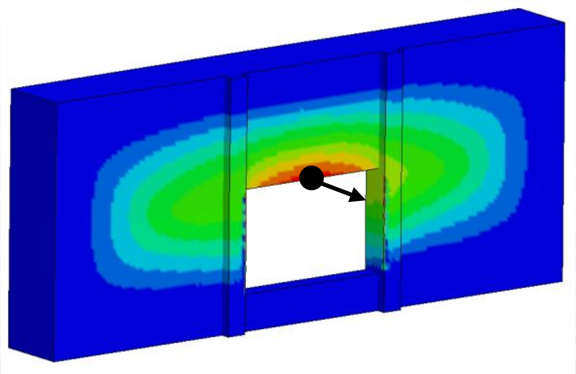
Load: 7-bar QD, p = 745 kPa, I = 170 kPa-ms/kg$^{1/3}$

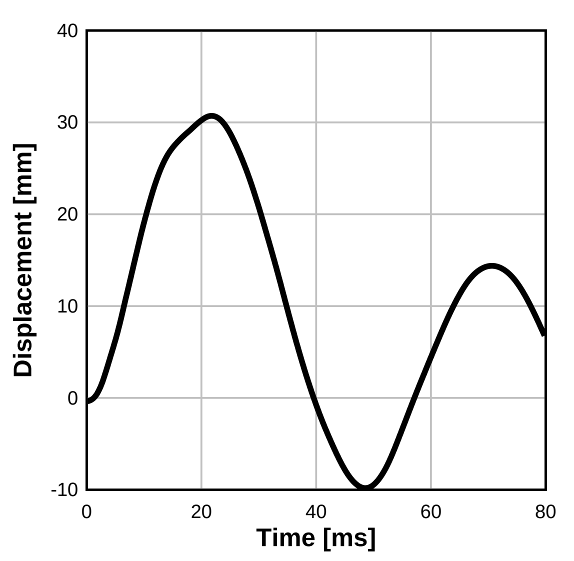
FE model - Headwall



Headwall Response







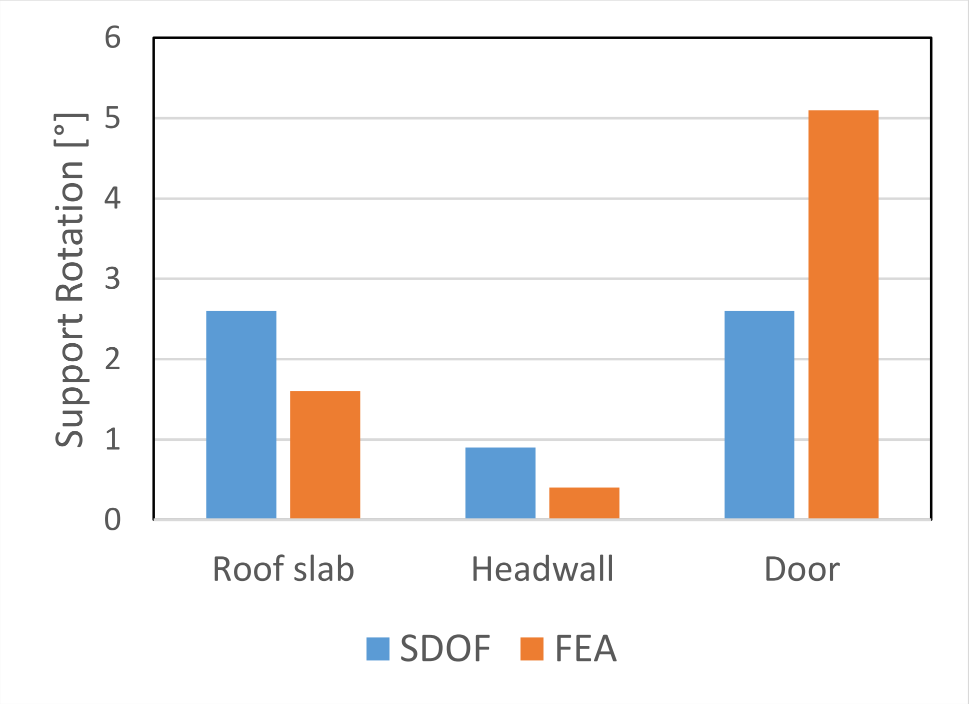
Load: 7-bar QD, p = 700 kPa, I = 200 kPa-ms/kg$^{1/3}$

Door Response

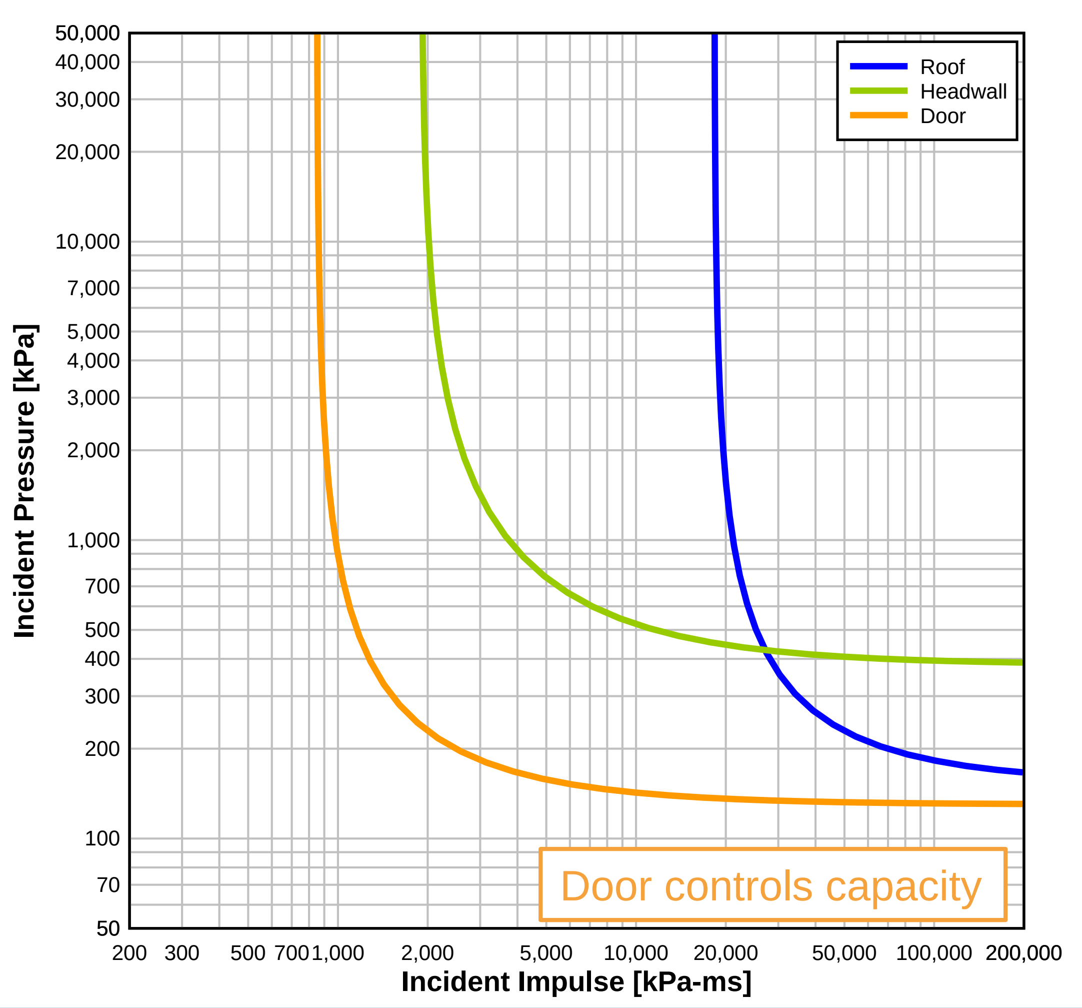
Deformations not exaggerated

Comparison of Analytical Methods

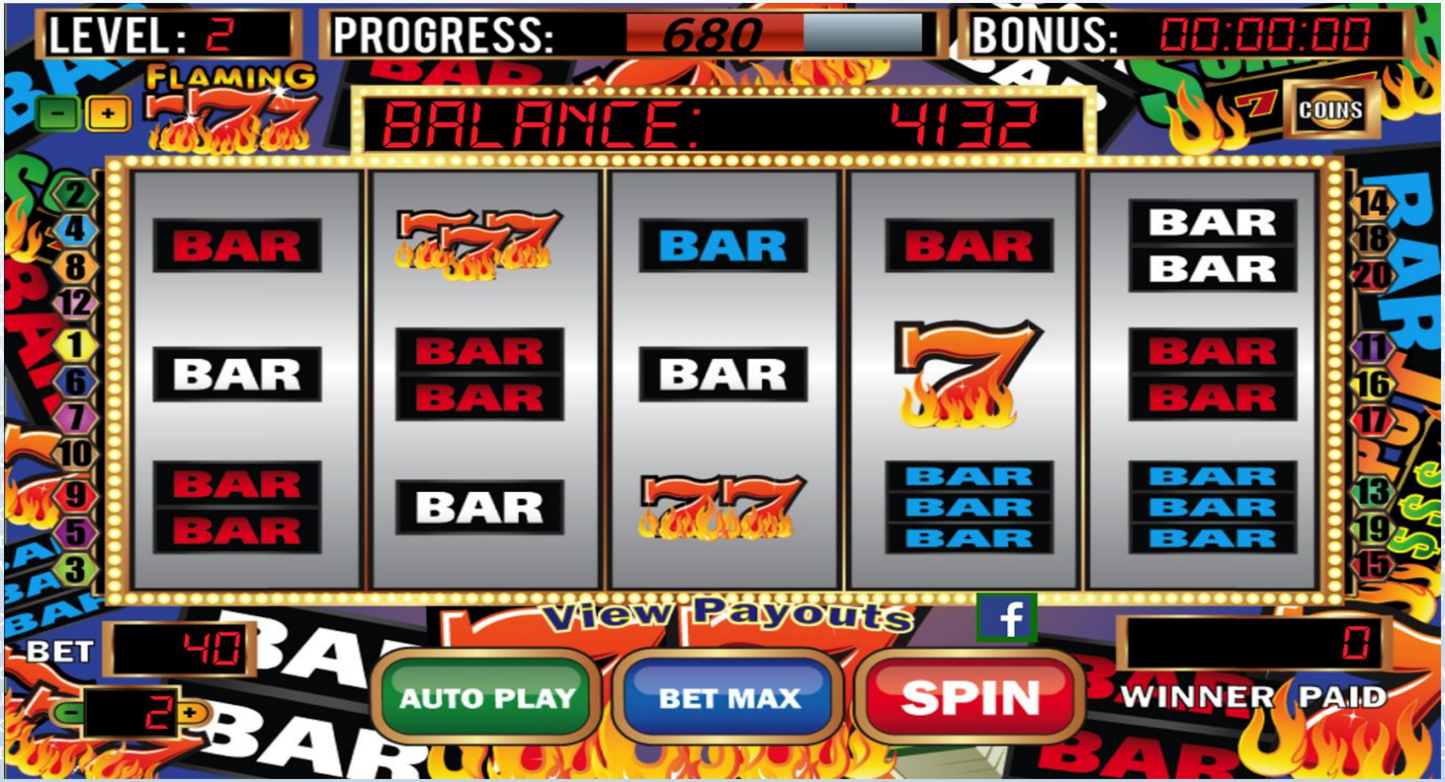
- Responses compared using the same (old) loads



Pressure-Impulse Curves



CLSECM – Bar Rating classification - 3 bar, 7 bar or ….???



Satisfaction of QD Design Requirements

Design	NEQ Rating [kg TNT]	Design Separations	QD 3 bar	QD 7 bar
Borden – Large Variant	250,000	OK ✓	OK ✓	NG ✗
Bedford – Small Variant	45,000	OK ✓	OK ✓	OK ✓

(✗) – failure of door

- Thus, large variant in its current configuration can only be treated as a 3-bar magazine
- Small variant can be treated as 7-bar

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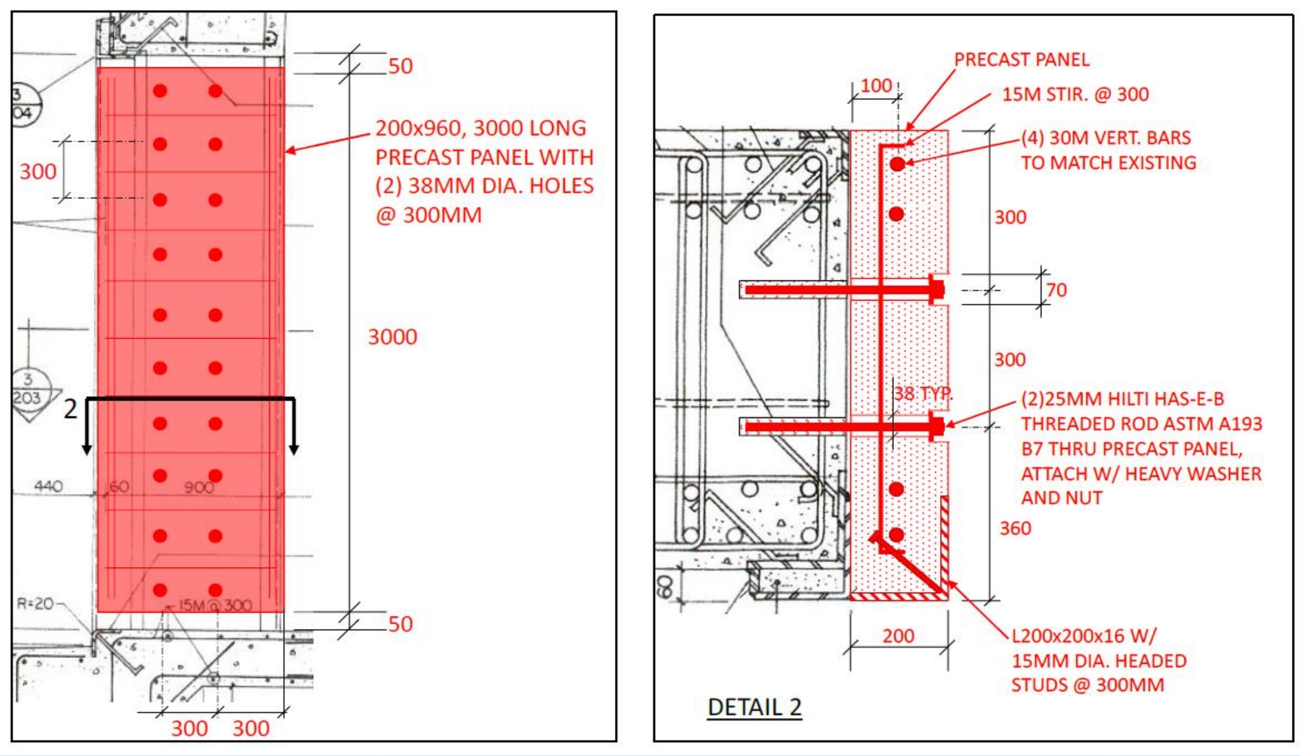
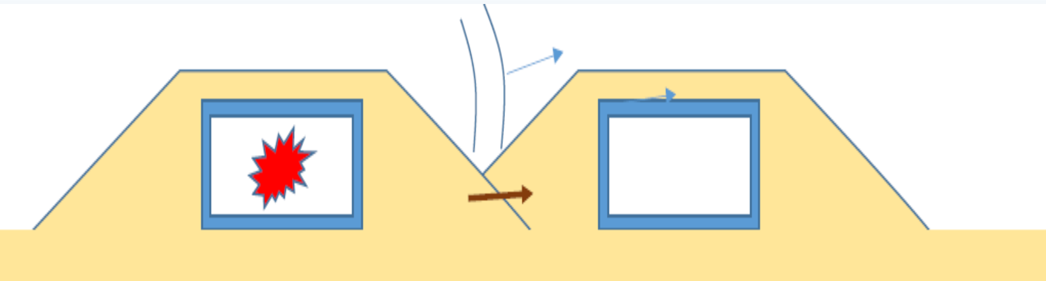
Remedial measure for door upgrade of large variant

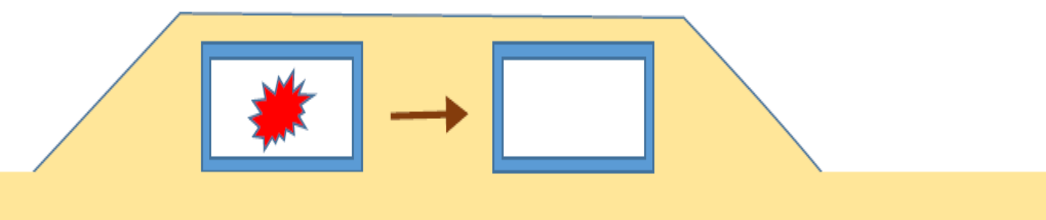


Attach precast concrete blocks to the pilaster to reduce the door opening to avoid shear failure

Effect of earth-fill overlap between CLSECMs located side-side



(b) ECMs with partially overlapping berms.



(c) ECMs with fully overlapping berms.

According to Canadian standard, based on NATO, amount of earth fill overlap impacts on the allowable NEQ as follows, based on the Q-D standard

- If overlap is < 0.5 H, no change in QD (D3)
- If overlap is >0.5 < 0.75 H, increase QD (D4)
- if overlap is > o.75 H, increase QD (D5),

where H is the height of structure;

D3 = 0.5 Q 1/3 (m/kg1/3); D4= 0.8; D5 =1.1

The above requirement is in conflict with the ECM design standard that only requires D3. Such requirement is not stipulated in the US DoD 4145.26 M-Contractor Safety Manual for Ammunition and Explosives, which permits solid backfill without restrictions.

Engineering study is to be commenced soon to assess the impact of earth fill overlap on the structural integrity of CLSECM.

Conclusions

- CLSECMs, as designed/constructed in early 1990s at specific separation distances, meet current day ECM standards and best practice
- The original design, based on decoupled components using SDOF analysis, is conservative and overdesigned as determined by recent assessment (2016/17) by LS DYNA using FEM models with coupled components.
- BEC 7.0 tool appears to be the best tool available to determine the blast loads from ECMs.
- Use of P-I curves for CLSECM should enable siting and licensing at various IMDs and NEQs, without the need for QD Table currently used.
- Suggest Standard writing authorities revisit the demand for designing ECMs for Bar Rating Loads. Instead, consider what is specified in the NATO document – Nationally Approved Structures for Explosives,

"when design environment criteria are available as continuous functions of NEQ and IMD, 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".

- Impact of earth fill overlap between CLSECMs is yet to be evaluated.