INTEGRATED APPROACH TO DYNAMIC IMPACT LOADING

DOE/NRC Natural Phenomena Hazards Meeting

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Simpson Gumpertz & Heger, Inc.
23 October 2018

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

Impact

- Impact loading is messy. We like to avoid impact loading if possible.
- With some nuclear structures, we have no choice.
- Sources of impact loading:
  - Tornado missile
  - Seismic
  - Accidental drop/strike

Source: New York Times

Traditional Approach to Impact

- Empirical formulae – focus on ballistic impact; useful for tornado missiles, etc.
- Hand calculations

BC-TOP-9A
Revision 2
SEPTEMBER 1974

TOPICAL REPORT
DESIGN OF STRUCTURES FOR MISSILE IMPACT

A REVIEW OF PROCEDURES FOR THE ANALYSIS AND DESIGN OF CONCRETE STRUCTURES TO RESIST MISSILE IMPACT EFFECTS*

R.P. KENNEDY
Holmes & Narver, Inc., Anaheim, California 92801, USA

Received 29 December 1975

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Vol. V:
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DEPARTMENT OF CIVIL ENGINEERING

Knoxville, Tennessee
September 15-17, 1980

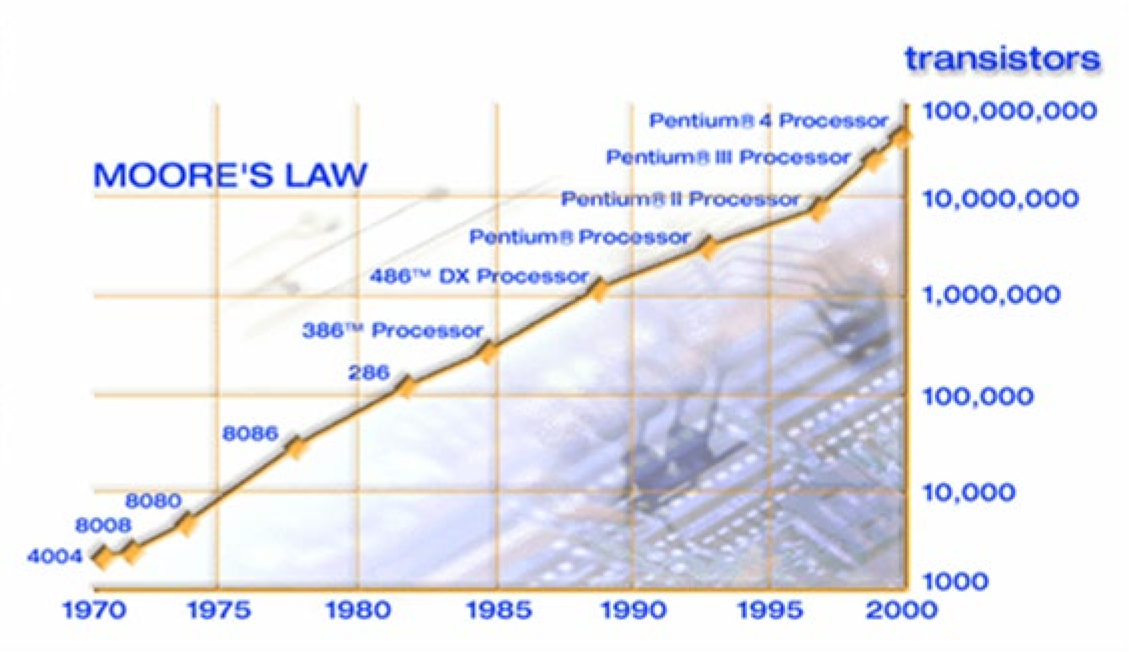
IMPACT EFFECT OF FRAGMENTS STRIKING STRUCTURAL ELEMENTS

By
R. A. Williamson
and
R. R. Alvy

Revised
November 1973

Recent Developments

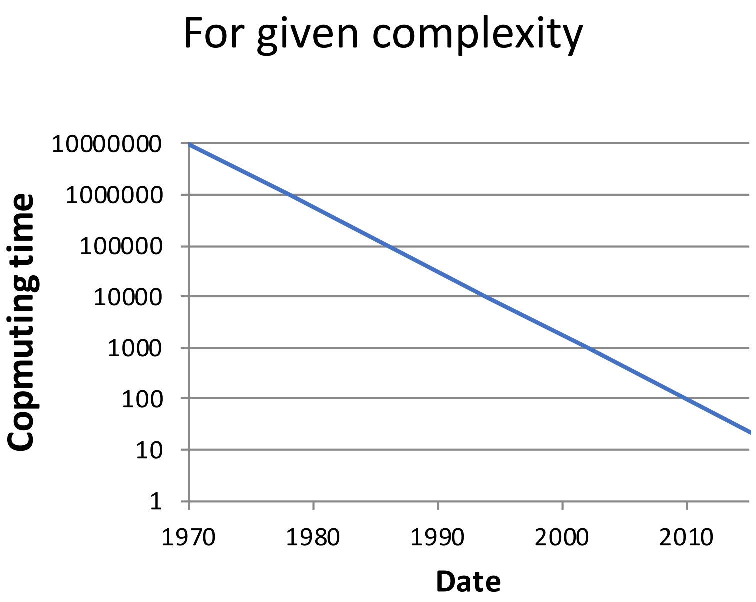
- Moore's Law:
  - The number of transistors in an integrated circuit doubles every two years
- What it means for engineers:
  - Increased computing power
  - Finite element analysis of nonlinear dynamic impact is feasible

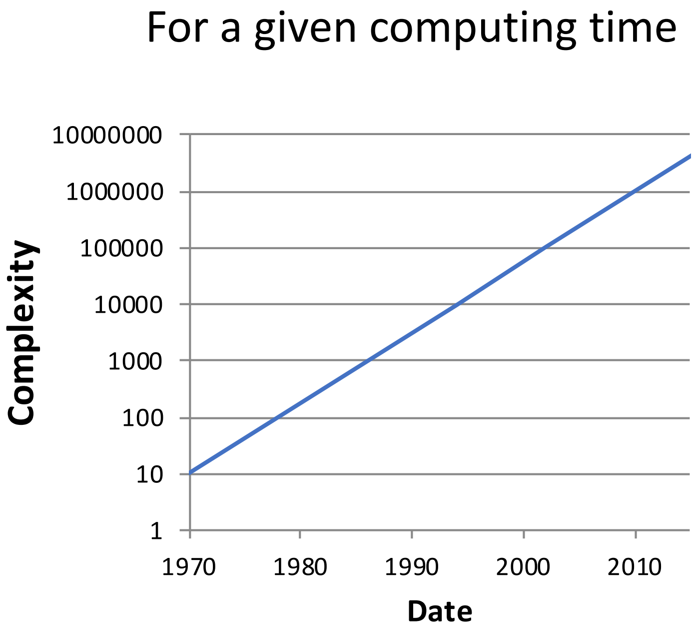


http://www.fnal.gov/

Recent Developments

- Moore’s Law for finite element analysis (FEA):





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Integrated Approach to Impact

- Point of impact evaluation
  - Local effects
  - Impulse load time history
  - Kinematics
- Overall “structural” evaluation
  - Single degree of freedom system
  - Multi degree of freedom system

Empirical formulae

Hand calculations

Linear static FEA

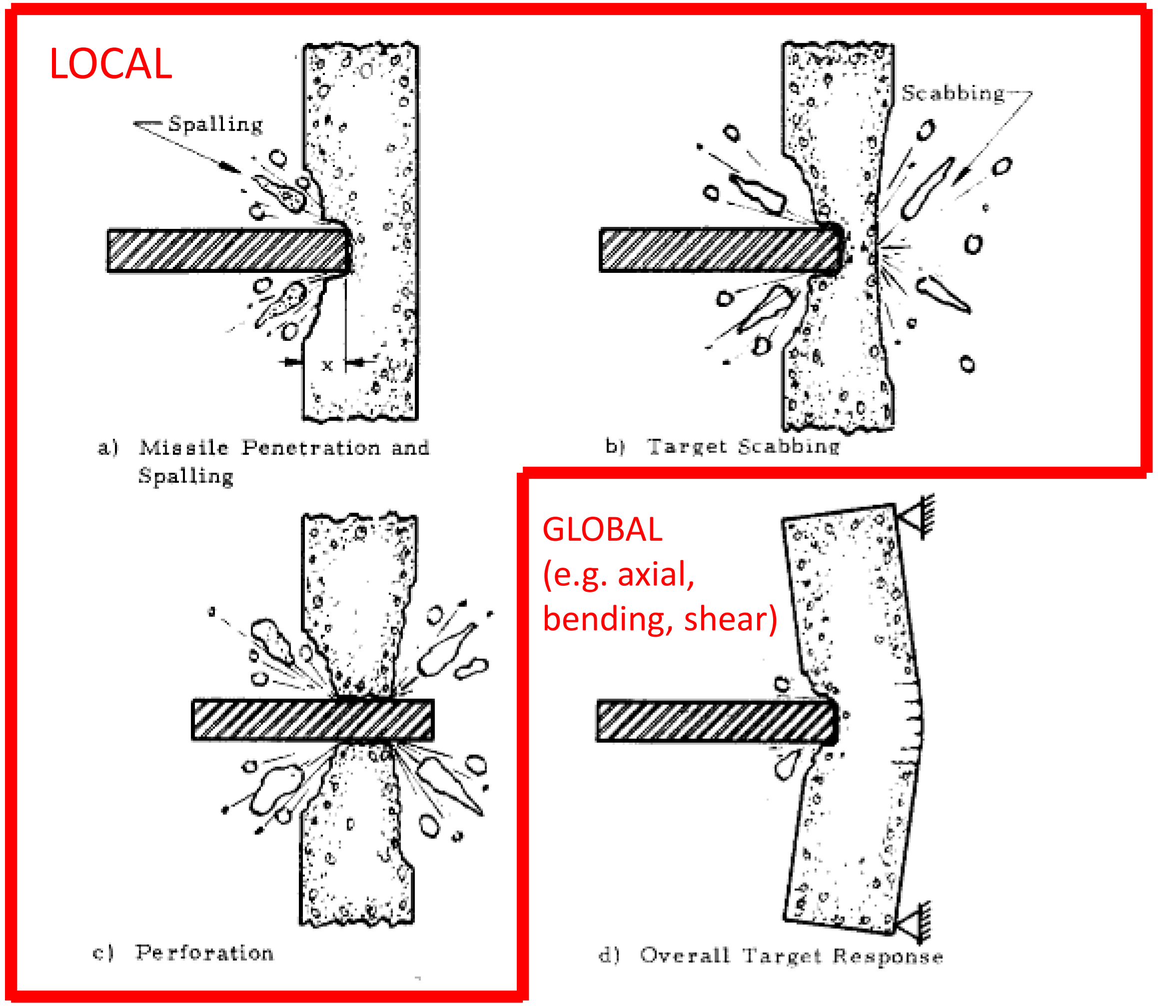
Linear dynamic FEA

Nonlinear dynamic FEA

Point of Impact Evaluation

- Local damage is important for high velocity, rigid “missile” striking massive targets
  - Important for tornado missile impact analysis
  - May also apply to other impact scenarios
- Evaluated using empirical formulae
- Interaction between local and global may be important

Kennedy (1975)



Empirical Formulae

- The most widely used empirical formulae are developed from extensive testing.
- Check that your selected formula has been verified over the range of parameters that you are considering.

Table 2
Comparison of predicted scabbing thickness versus test results for Calspan tests.

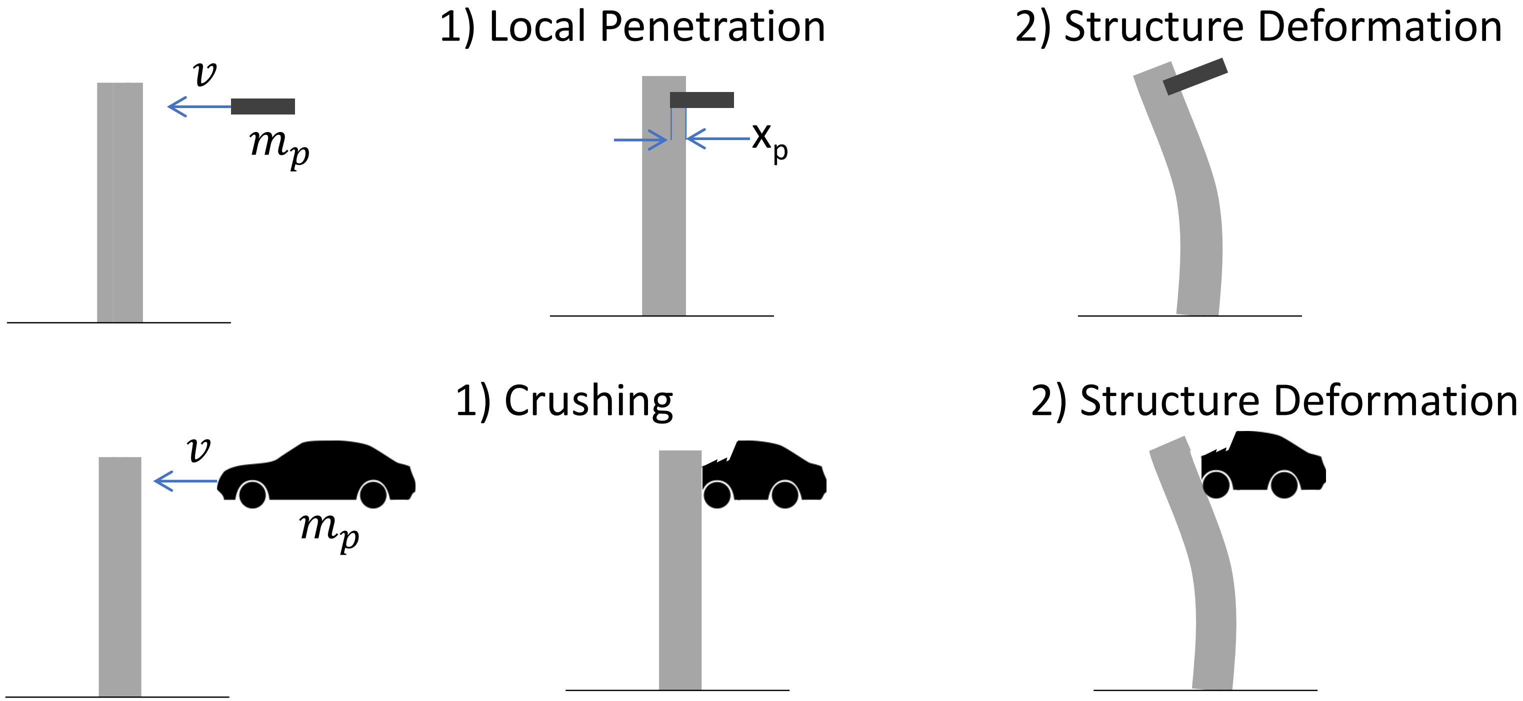
Kennedy (1975)

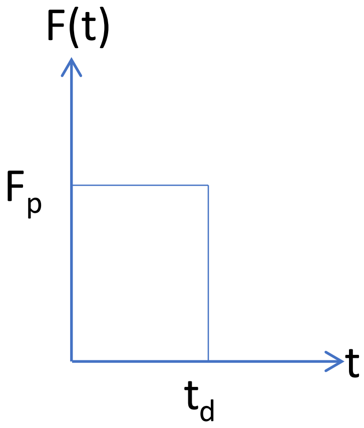
Missile	Velocity (ft/sec)	Calspan test results (table 2)	Scabbing thickness (inches) Modified Petry I (K_p = 0.00426) (eqs (1) & (3)) Pre-dicted	Ratio pred./test	Modified Petry II (K_p = 0.0022) (eqs (1) & (3)) Pre-dicted	Ratio pred./test	Army Corps of Engineers (eqs (4) & 6)) Pre-dicted	Ratio pred./test	Modified NDRC (eqs (7) & (6) or (10)) Pre-dicted	Ratio pred./test	Modified BRL (eqs (13) & (14)) Pre-dicted	Ratio pred./test
213 lb steel slug	100	12.0	1.4	0.12	0.7	0.06	23.3	1.94	14.2	1.18	2.8	0.23
	200	18.0	5.1	0.28	2.6	0.14	24.9	1.38	21.6	1.20	7.2	0.40
	350	24.0	13.4	0.56	6.9	0.29	28.2	1.18	26.1	1.09	15.1	0.63
	mean ratio pred./test			0.32		0.16		1.50		1.16		0.42
207 lb steel pipe	180	12.0	24.3	2.02	12.5	1.04	19.5	1.62	14.0	1.17	30.3	2.52
	320	18.0	67.5	3.75	34.9	1.94	33.7	1.87	19.3	1.07	65.1	3.62
	470	24.0	122.5	5.10	63.3	2.64	52.8	2.20	27.1	1.13	108.6	4.52
	mean ratio pred./test			3.62		1.87		1.90		1.12		3.55
132 lb steel pipe	400	18.0	61.4	3.41	31.7	1.76	31.0	1.72	18.9	1.05	55.9	3.11

R.P. Kennedy / Design of concrete structures to resist missile impact

Impulse Load Time History

- When there is significant penetration or crushing at the point of impact, the impulse load time history can be determined by “decoupling” the local and overall phases.
- The simplest method approximates the impulse as a constant force. The force may also be linear with respect to deformation/penetration, which would produce a sinusoidal time history.
- The work done by this force balances the missile kinetic energy – x_p can be calculated from empirical formulae for penetration OR F_p can be taken equal to the crush capacity.





$$F_p \cdot x_p = \frac{1}{2} \cdot m_p \cdot v^2$$

$$F_p \cdot t_d = m_p \cdot v$$

Kinematics

- When impulse load time history cannot be readily determined, the impact could be modeled as “pure impulse” (with infinitesimal duration) by using the velocity just *after* impact must be calculated.
- The two unknowns ($v_{\mathrm{a}2}$ and $v_{\mathrm{b}2}$) may be determined by considering conservation of momentum (1) and coefficient of restitution, e_r (2).
- e_r is the ratio between the relative “departing” and “approaching” velocities of the impacting objects. It is always between 0 and 1.

(1) $m_a \cdot v_{\mathrm{a}1} + m_b \cdot v_{\mathrm{b}1} = m_a \cdot v_{\mathrm{a}2} + m_b \cdot v_{\mathrm{b}2}$

(2) $e_r = \dfrac{v_{a2} - v_{b2}}{v_{\mathrm{b}1} - v_{a1}}$

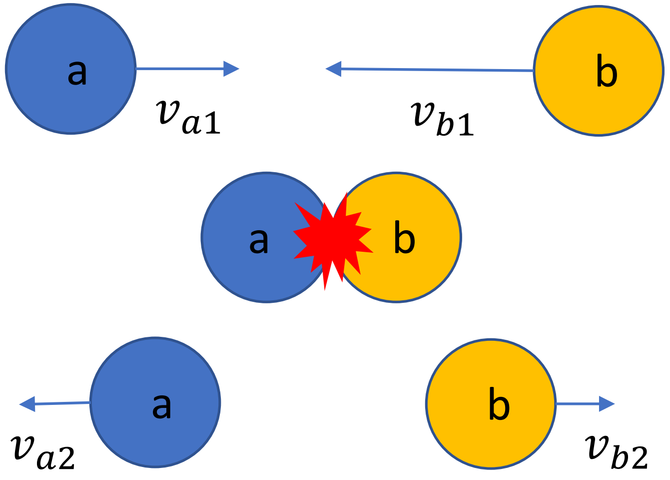
Tip: Use relative velocity to simplify the equations.

$v'_{\mathrm{a}1} = v_{\mathrm{a}1} - v_{\mathrm{b}1}$

$v'_{\mathrm{b}1} = v_{\mathrm{b}1} - v_{\mathrm{b}1} = 0$

Before impact:
“Approaching”

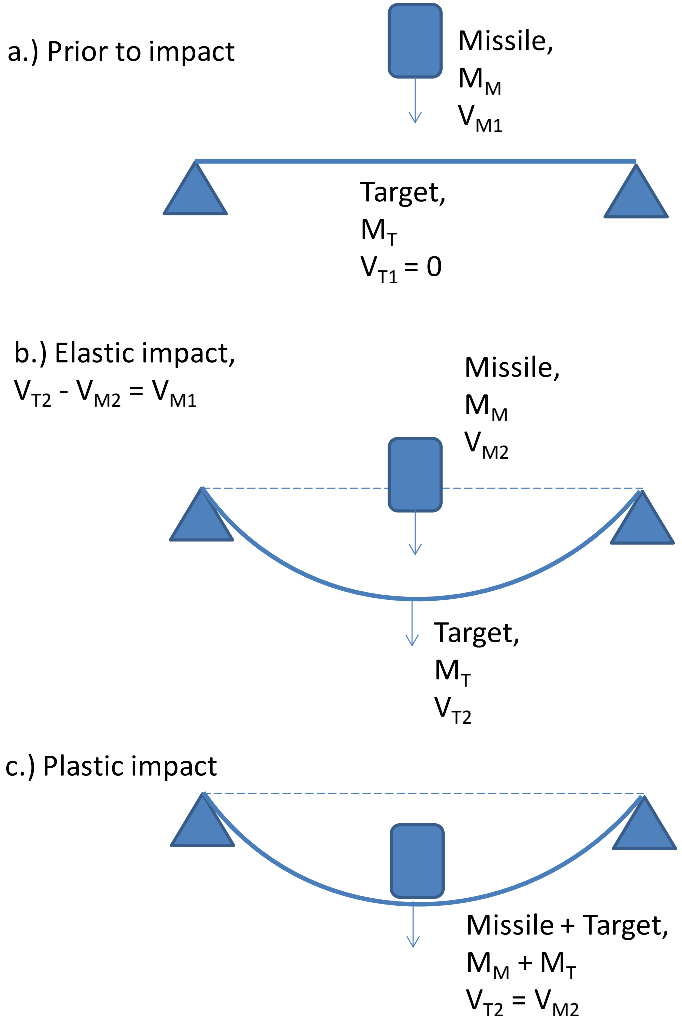
After impact:
“Departing”



Note: v_{b1} and $v_{\mathrm{a}2}$ would have a negative sign

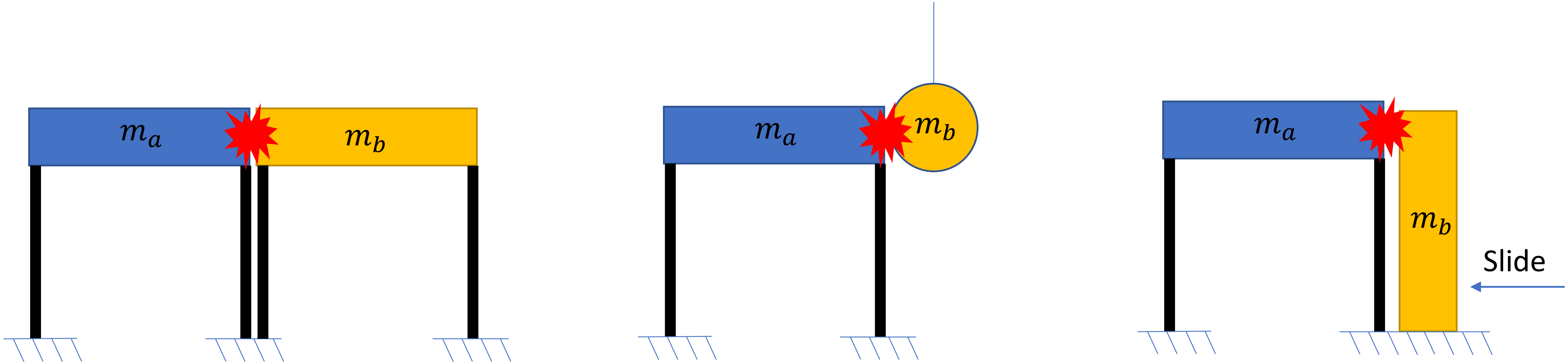
Coefficient of Restitution

- Perfectly elastic impact, $e_r = 1$ (approaching velocity equals departing)
- Perfectly plastic impact , $e_r = 0$ (the two objects "stick" together)
- Empirical information is available for values in between 0 and 1, depending on the structures and materials involved in the impact.



System Simplification

- Once the impulse load time history or velocity *just* after impact is known, the dynamic response may be determined from simple structural dynamics for a single degree of freedom system.
- For many impact scenarios, the systems are easily reduced to a single degree of freedom
- The masses of the impacting objects are self-evident in these cases.



System Simplification

- For systems with distributed mass and stiffness (such as walls and slabs), mass and stiffness could be approximated by selecting a mode shape, ϕ corresponding to the impact deformation.

$$m^* = \sum_i m_i \phi_i^{\,2} \qquad (7)$$

$$k^* = \sum_i k_i (\Delta\phi_i)^2 \qquad (8)$$

$$p^* = \sum_i p_i \phi_i \qquad (9)$$

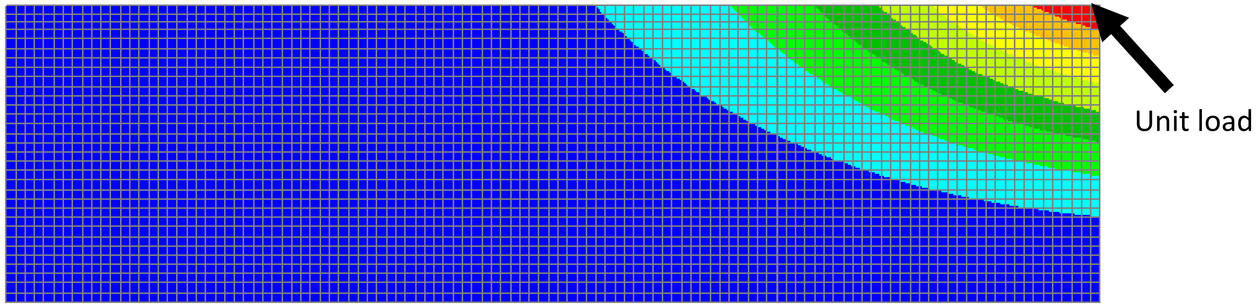
ASCE (1975)

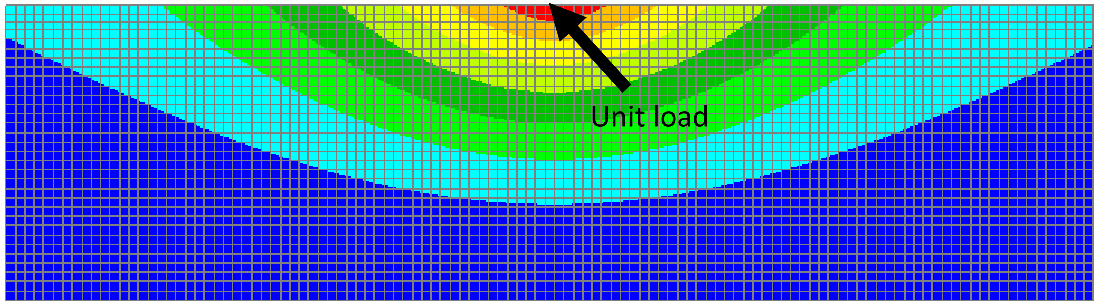
- Values in the above equations (m_i, k_i, p_i, ϕ_i) may be determined from literature or from linear FEA

System Simplification

- Use of static linear FEA allows for generalized modes for a wide range of structural configurations. Multiple impact locations can also be considered and quickly processed.
- Check if the mode shape is valid: compare strain energy distribution in the structure to the extent of wave propagation over the impact duration.

Cantilever wall with impact at top corner and top mid-span:





Dynamic Response

- The linear dynamic amplification factor for impulse loading on a single-degree-of-freedom system can be simply determined from structural dynamics.
- The calculated dynamic amplification factor can be used with the prior FEA results to determine structural demands from impact.

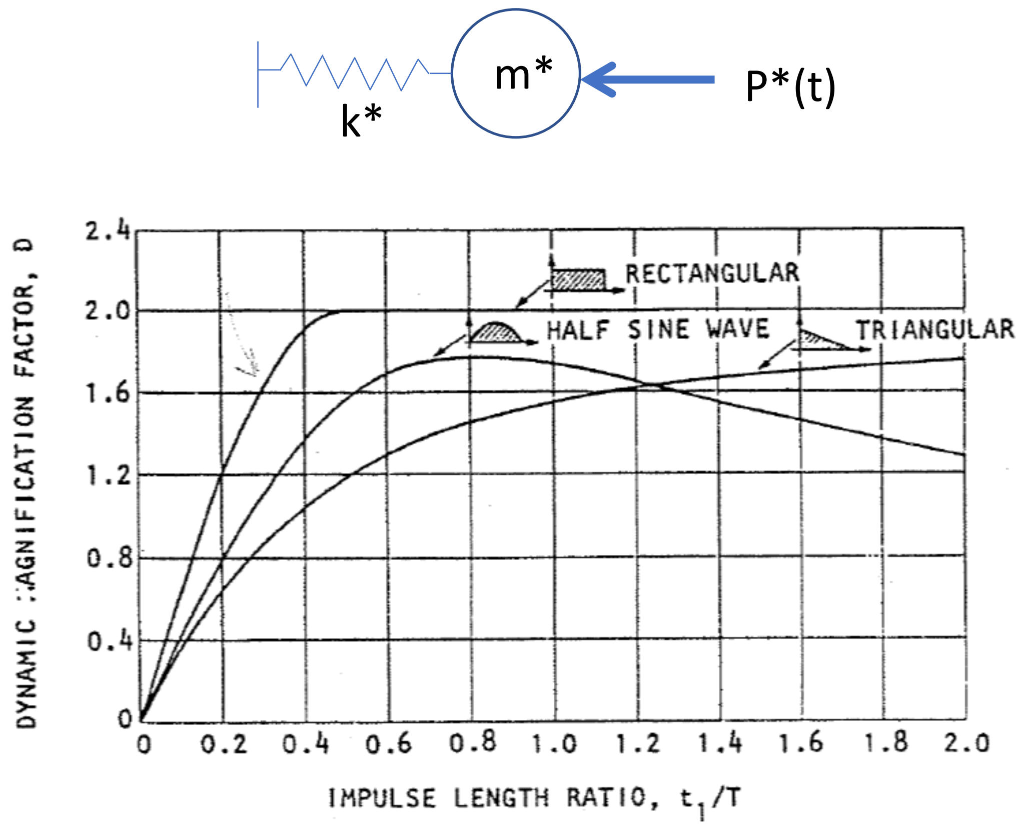
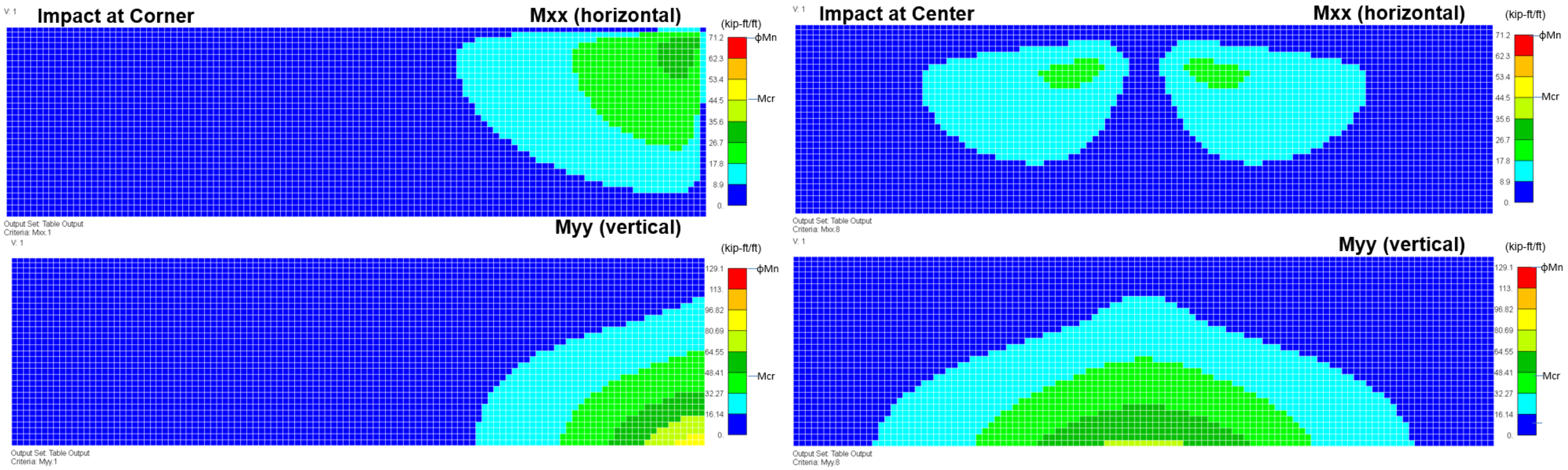


FIGURE 3.1.4 DISPLACEMENT-RESPONSE SPECTRA (SHOCK SPECTRA) FOR THREE TYPES OF IMPULSE

ASCE (1975)

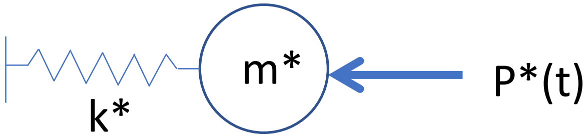
Dynamic Response

- Moments in cantilever wall due to impact:



Nonlinear Dynamic Response

- The same parameters can be used for nonlinear structural response.
- The required ductility for a given impact load can be calculated from single degree of freedom response.
- Where impulse load time history is not know, the energy absorption capacity of a structure may be determined from yield line analysis or by nonlinear "pushover" type analysis (resistance function).



Biggs (1964)

72 *Introduction to Structural Dynamics*

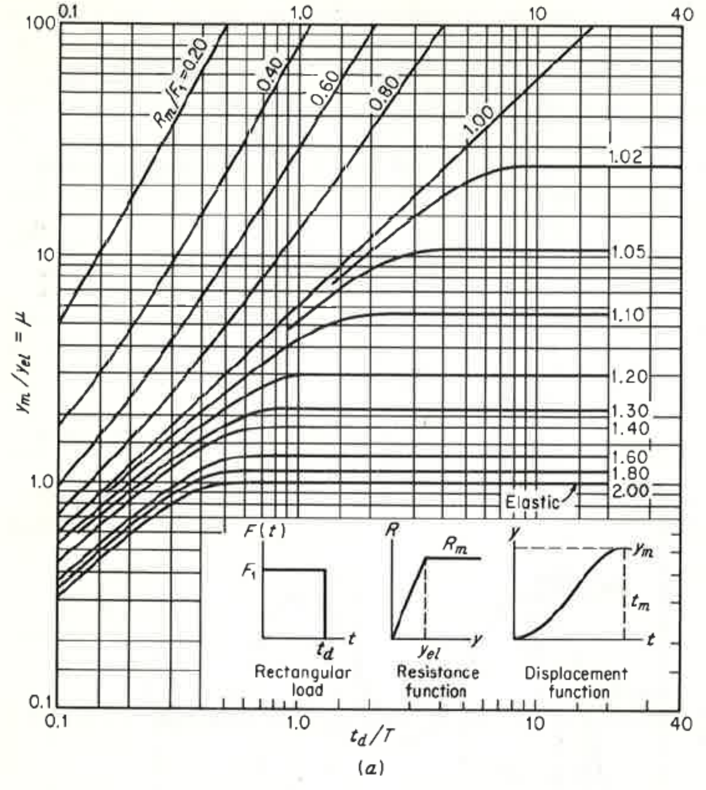


FIGURE 2.23 Maximum response of elasto-plastic one-degree systems (undamped) due to rectangular load pulses. (*U.S. Army Corps of Engineers.*[10])

Kennedy (1975)

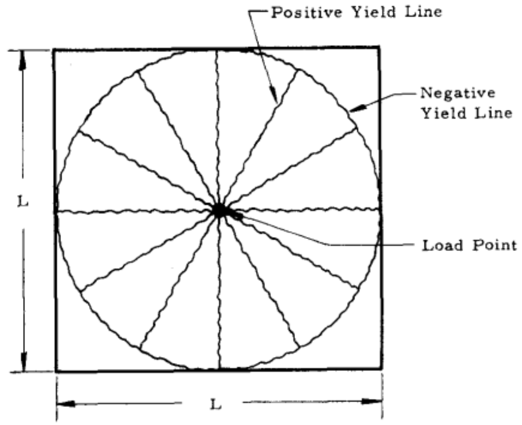
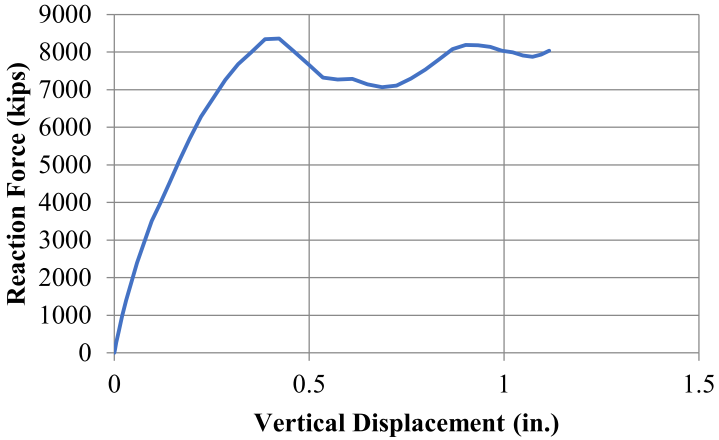


Fig. 6. Yield pattern for concentrated load at center of square slab with restrained edges.



Integrated Approach to Impact

- <u>Point of impact evaluation</u>
  - Local effects
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- <u>Overall "structural" evaluation</u>
  - Single degree of freedom system
  - Multi degree of freedom system

Empirical formulae

Hand calculations

Linear static FEA

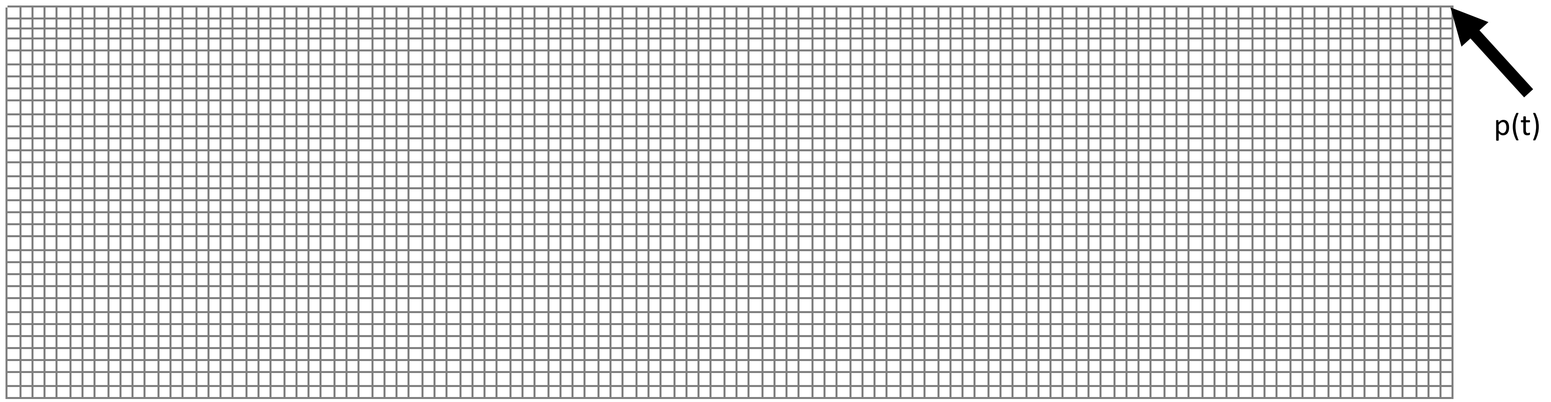
Linear dynamic FEA

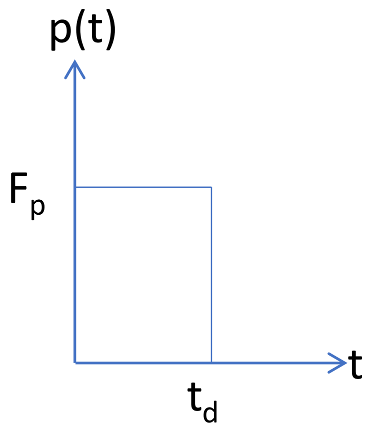
Nonlinear dynamic FEA

Linear Dynamic FEA

- If the impulse load time history is known, but the system cannot be reduced to single degree of freedom, then linear dynamic FEA may be used.
- This method accounts for the action of multiple modes.

Cantilever wall with impact at top corner:



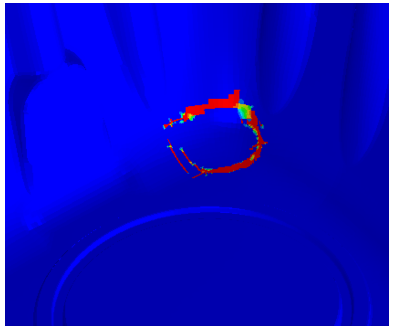


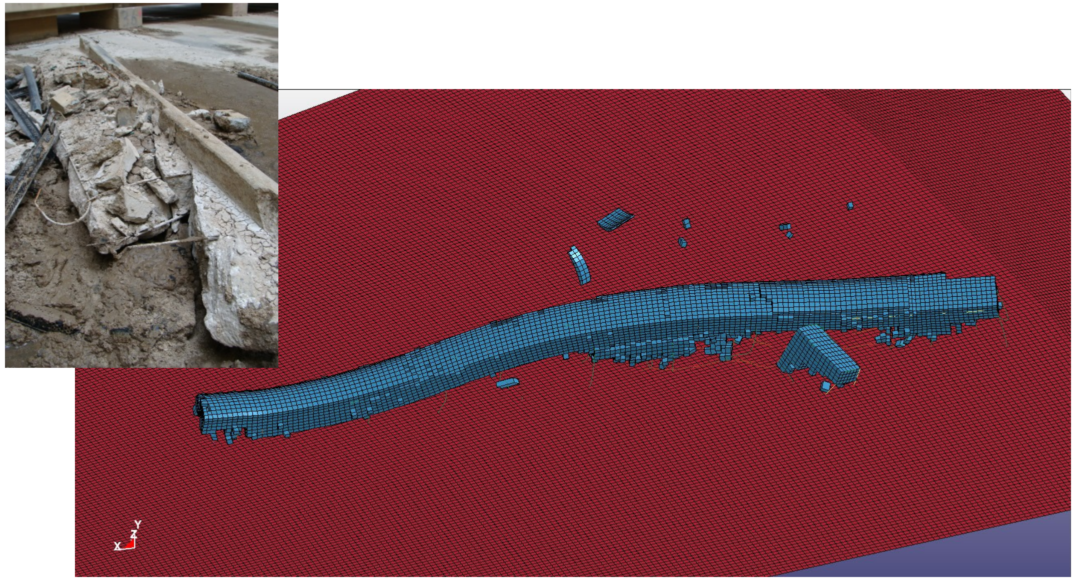
Nonlinear Dynamic FEA

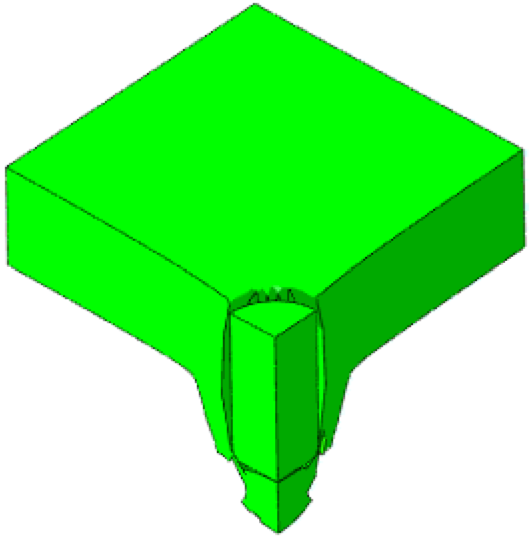
- It is appropriate to use nonlinear dynamic FEA if:
  - The system cannot be reduced to single degree of freedom

  AND

  - The impulse load time history is not known
- Nonlinearity may come from contact, material behavior, and/or rigid body motion.







Nonlinear Material Properties

- It is important to select nonlinear material properties carefully.
- Include high strain rate effects
  - Typically, reduced ductility and increased strength/stiffness
- Include triaxiality effects
  - Reduced ductility for steel; hydrostatic pressure “cap” for concrete
  - High triaxiality at the point of impact
- Material models for impact:
  - Concrete: Material Model 159 in LS-DYNA
  - Steel: Johnson-Cook
  - Polymer Composites: Modified Hashin

Conclusions

- Engineers have many tools at our disposal for solving impact problems.
- These tools will continue to become more efficient and more sophisticated.
- An integrated approach to impact gives these sophisticated tools a firm grounding in traditional mechanics-based and empirical approaches.
  - Or better yet, solve the problem without turning on your computer.

- Note: there is no cookbook approach to impact. Unique problems require unique solutions.

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