Design of automotive body structures for crashworthiness

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Outline

- **Introduction**
- **Related work**
- **Crush modes**
- **Equivalent mechanism (EM) model**
- **EM-based crashworthiness design**
- **Case study**
- **Summary**
- **Highlights of related projects**
- **Closure**

Introduction

- **Car accidents kill….**

Introduction

- **Crash safety in passenger vehicles**
  - Government regulations
  - Insurance standard (more strict than government)
  - Passive (crashworthiness design)
  - Active (air bags, seat belts, ABS, drive-by-wire, etc.)
- **Crashworthiness is a "must-meet" criterion**
  - Constraint, rather than objective
  - Cannot sell a vehicle without passing government tests

Introduction

- **Crashworthiness design is difficult…**
  - Complex nonlinear dynamics
    - “crushing coke cans”
  - Contradictory requirements
    - Stiffness for occupancy protection
    - Compliance for energy absorption
  - Body is only a part of vehicle
    - Must realize inexpensively
    - Must realize with lightweight

Introduction

- **Crash tests: takes too much $$**

Introduction

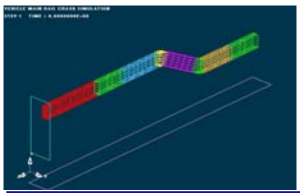
- **Nonlinear FE simulations: takes too long time**

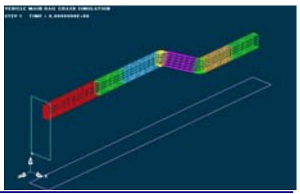
Related work

- **Size optimization of nonlinear FE models.**
  - Yang, Gu, Tho and Sobieski (2001), Han and Yamada (2000), Kurtaran, Omar and Eskandaren (2001), Chen (2001), Andersson et al. (2003)
- **Topology optimization of 2D models**
  - Mayer, Kikuchi, and Scott (1996), Soto and Diaz (1999), Luo, Gea, and Yang (2000), Mayer, Maurer and Bottcher (2000), Pedersen (2003), Soto (2003).
- **Optimization with surrogate/reduced-order/lumped models.**
  - Wang and Landry (1991), Bennett, et al. (1991), Yang, et al. (2001), Chappella and Diaz (2002), Jones (2003), Takada and Abramowicz (2004).

Crush modes

- **Crush modes (CM) of a structure**
  - Time-space pattern of primitive modes (crushing and bending)
  - Strong indication of energy absorption characteristics
  - Good CM ~= more crushing at the beginning
  - Utilized by experienced engineers as a design guide via crush mode matching





Crush modes

- **Crush mode matching: common design practice**
  - Steps:
    1. Guess the ideal CM of a given structure
    2. Examine crush simulation of an FE model; observe CM
    3. Modify the FE model until its CM matches to the ideal CM
  - Very effective if:
    - The guessed ideal CM is in fact good
    - The initial design is close to the ideal design
  - But often
    - The ideal CM is difficult to guess for complex structure
    - The ideal CM is difficult to realize by ad-hoc design modifications

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Crush modes

- **Crush mode matching: computational emulation**
  - Steps:
    1. Optimize an fast approximate model to obtain the ideal CM
    2. Realize the optimized approximate model as an FE model
    3. Modify the FE model until its CM matches to the CM of the optimized approximate model
  - Advantages:
    - No need to guess the ideal CM: obtained by the optimization of fast approximate model
    - Easy to match to the ideal CM: an initial FE model is already close to the ideal design

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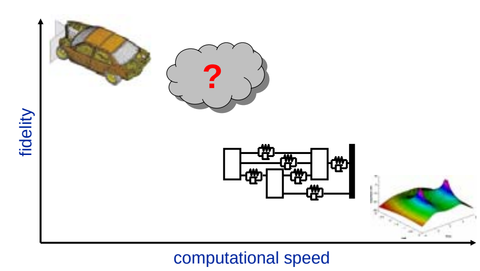
Equivalent mechanism (EM) model

- **"Dream model" for crush mode matching**
  - Can express the same CMs as FE models
  - Easy to realize to a FE model



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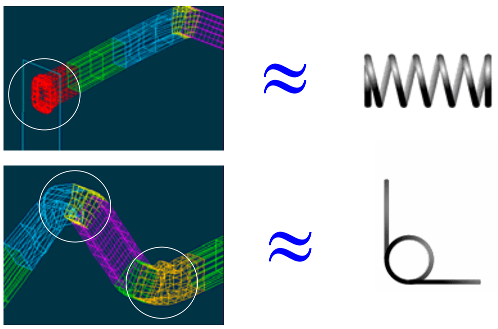
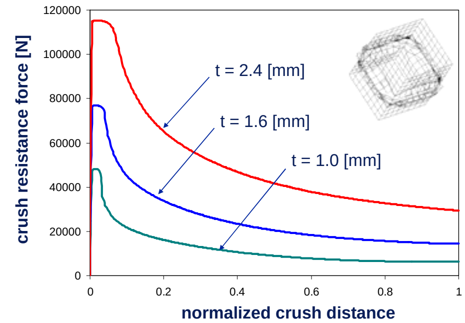
Equivalent mechanism (EM) model

- **Two "primitive" joint types of EM models**



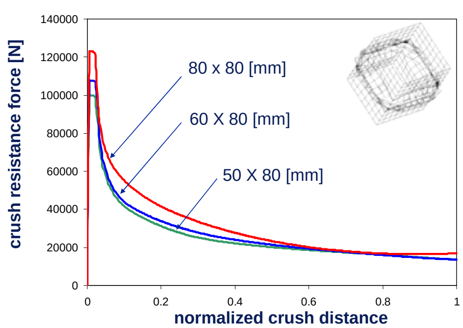
Equivalent mechanism (EM) model

- **Axial crush of 50x50 [mm] box section (steel)**



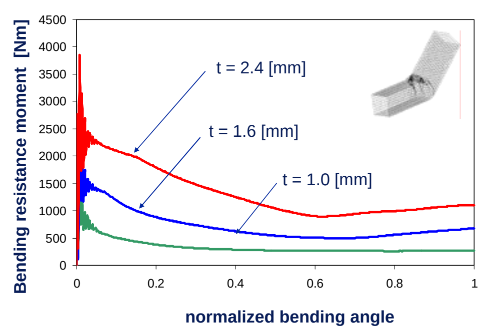
Equivalent mechanism (EM) model

- **Axial crush of 1.6 [mm] thick box section**



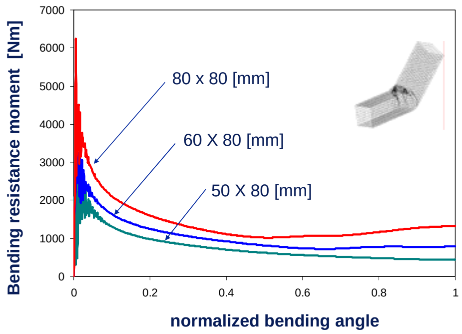
Equivalent mechanism (EM) model

- **Transversal bending of 50x50 box section**



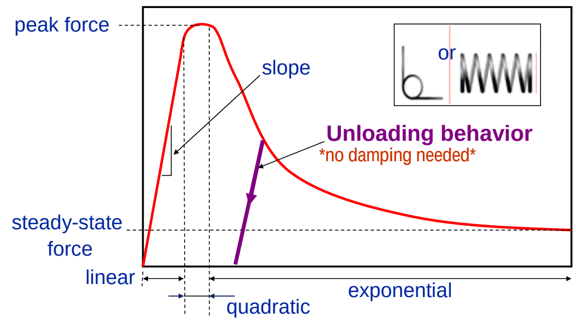
Equivalent mechanism (EM) model

- **Transversal bending of 1.6 [mm] thick box section**



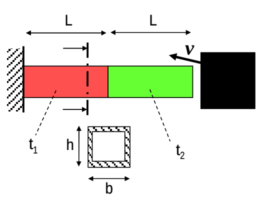
Equivalent mechanism (EM) model

- **Parameters of nonlinear spring characteristics**



Equivalent mechanism (EM) model

- **Model validation**
  - 2-Part beam subjected to offset impact
  - EM and FE runs for full factorial designs (1536 samples)
    - 4 Levels on t1, t2, h, b
    - 3 Levels on h/L
    - 2 Levels on v
  - Results compared statistically

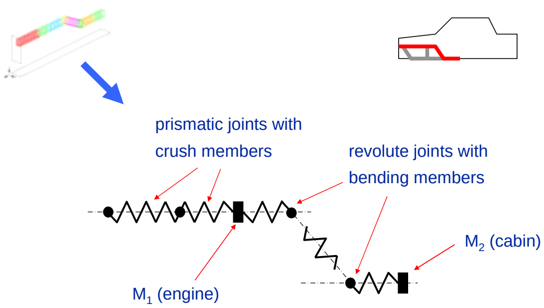


Equivalent mechanism (EM) model

- **Model validation**
  - Average absolute positional error = 3.8% of column length
  - Std. dev. of absolute positional error = , 2.7% of column length
  - Good average absolute error (<6.0%) on a large percentage (85%) of samples
  - Accuracy in some samples is bad (10% or more), when the CM is not captured correctly

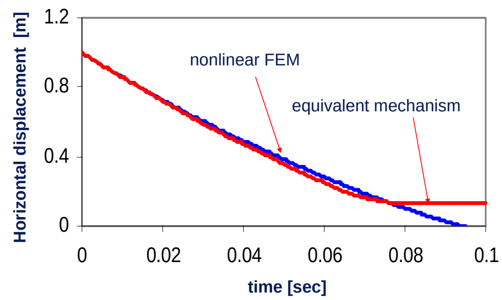
Equivalent mechanism (EM) model

- EM model of main rail



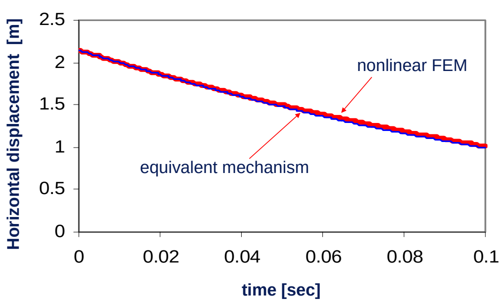
Equivalent mechanism (EM) model

- Horizontal displacement of engine mass



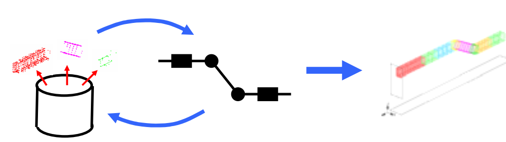
Equivalent mechanism (EM) model

- Horizontal displacement of cabin mass

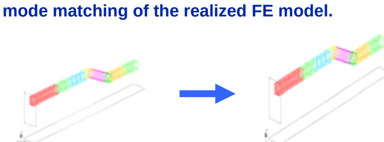


EM-based crashworthiness design

1. Optimization of EM model with FE component database

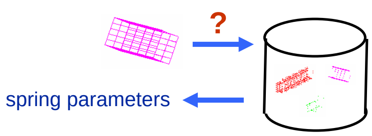


2. Crush mode matching of the realized FE model.



EM-based crashworthiness design

- **FE component database**
  - Input: Dimensions of FE components (w, h, t, etc.)
  - Output: Nonlinear spring parameters (peak force, elastic slope, steady-state force, etc.)
  - Implementation: RBNN trained with FEA results of sample components



EM-based crashworthiness design

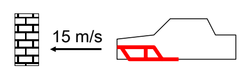
- **Step 1: Optimization of EM model**
  - Input:
    - Frame topology and joint locations (prismatic & revolute)
  - Design variables:
    - Cross sectional dimensions of structural frames
  - Constraints:
    - Displacement, acceleration
  - Objective (minimization):
    - Structural weight
  - Exploration of CM with a short (~120 X 5) GA run
  - "Built-in" realization to a FE model: Simply assemble FE components in the database

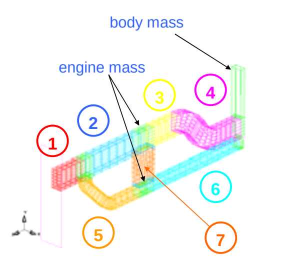
EM-based crashworthiness design

- **Step 2: Crush mode matching of FE model**
  - Design variables:
    - Cross-sectional dimensions of components (w, h, t, etc)
  - Initial design:
    - FE realization of the optimal EM
  - Target CM:
    - CM of the optimized EM
  - Initial design is likely already good – a few iterations for final tuning.

Case studies

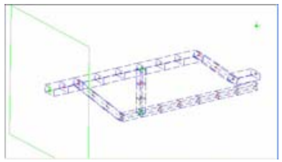
- **Case study 1: problem**
  - 2D front substructure
  - Design variables (11)
    - thicknesses of components 1-7
    - Cross section width and height of components 1-4.
    - Cross section width and height of components 5 and 6.
  - Objectives
    - Minimize weight [kg]
  - Constraints
    - Frontal intrusion < 0.95 [m]
    - Cabin intrusion < 0.1 [m]

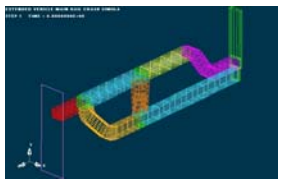




Case studies

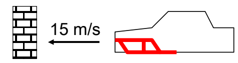
- **Case study 1: result**
  - 10 % weight reduction from the best design by EM/GA+FE/SQP (Hamza and Saitou, 2003)
  - Only 6 FE simulations in CM matching (compared to 150 by EM/GA+FE/SQP)

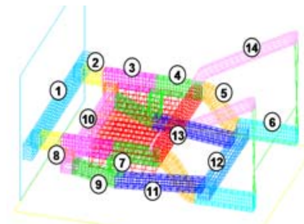




Case studies

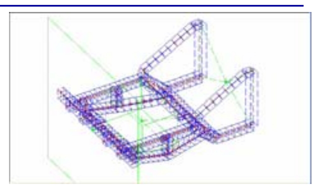
- **Case study 2: problem**
  - 3D front substructure
  - Design variables (18)
    - Thicknesses 1 – 14
    - Cross section width and height of upper and lower frames
  - Objectives
    - Minimize weight [kg]
  - Constraints
    - Cabin intrusion < 0.1 [m]
    - Cabin acceleration < 30 [G]

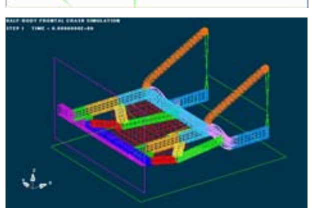




Case studies

- **Case study 2: result**
  - 5% weight increase from the best design by FE/GA
  - 40% decrease in cabin intrusion from FE/GA
  - 3% increase in acceleration from FE/GA
  - Only 10 FE simulations in CM matching (compared to 50X10=500 by FE/GA)
  - yet to improve…



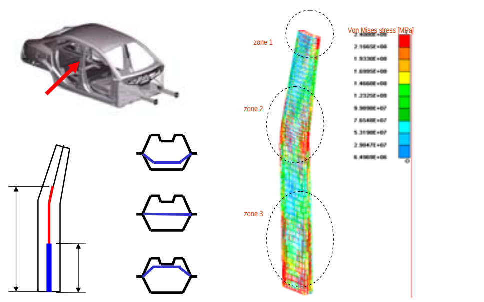


Summary

- **Equivalent mechanism (EM) model**
  - Reduced order model with high geometric fidelity
  - Nonlinear springs at prismatic and revolute joints
  - Can express crash modes (CM)
- **EM-based crashworthiness design**
  - Exploration of CM by a short GA run
  - "Database-in-loop" optimization of EM for easy realization as FE models.
  - CM matching of FE model for final tuning.
- **For more details:**
  - Hamza, K. and Saitou, K., 2004, "Design for Crashworthiness of Vehicle Structures via Equivalent Mechanism Approximations," Proceedings of the *2004 ASME International Mechanical Engineering Congress and R&D Expo*, Anaheim, California, November 13-19.

Highlights of related projects

- **B-pillar reinforcement design against side impact**
  - Student: Karim Hamza



Highlights of related projects

- **Publications**

  - Hamza, K. and Saitou, K., 2003 " Design for Structural Crashworthiness using Equivalent Mechanism Approximations," Proceedings of the *2003 ASME Design Engineering Technical Conferences*, Chicago, Illinois, September 2-6, DETC2003/DAC-48751. Also to appear as Hamza, K. and Saitou, K., "Design for Structural Crashworthiness using Equivalent Mechanism Approximations," *Transactions of ASME, Journal of Mechanical Design*.
  - Hamza, K., Saitou, K., and Nassef, A., 2003, " Design Optimization of A Vehicle B-Pillar Subjected to Roof Crush using Mixed Reactive Taboo Search," Proceedings of the *2003 ASME Design Engineering Technical Conferences,* Chicago, Illinois, September 2-6, DETC2003/DAC-48750.
  - Hamza, K. and Saitou, K., 2004, "Crashworthiness Design Using Meta-Models for Approximating of Box-Section Members," Proceedings of the *8th Cairo University International Conference on Mechanical Design and Production*, Cairo, Egypt, January 4-6, vol. 1, p. 591-602.
  - Hamza, K. and Saitou, K., 2004, "Crash mode analysis of vehicle structures based on equivalent mechanism approximations," Proceedings of the *Fifth International Symposium on Tools and Methods of Competitive Engineering*, Lausanne, Switzerland, April 13 - 17, p. 277-287.

Acknowledgement

- **"Powered" by…**

Nissan Technical Center North America, Inc.

Closure

- **For more information:**
  - http://www-personal.engin.umich.edu/~kazu/publications.htm
  - kazu@umich.edu