Sustainable Design:
The Construction Industry

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**Global Impact:**

**the ‘Standard Run’**

**Assumptions:**
- ‘continue historical path as long as possible - no major change’
- growth continues until environmental and resource constraints finally limit it

**Results:**
- irreversible environmental changes occur
- investment capital depreciates faster than it can be re-built
- as it falls, food and health services fall too
- death rates increase and life expectancy reduces

(From ‘Beyond the Limits’, 1998)
Use of Raw Materials in the US
Average US House Sizes Tripled in 50 Years

Photographs of small and large houses.
Images removed for copyright reasons.

~800 square feet  ~2400 square feet
The earth is finite...

....natural resources have a limit
Whole Life Design

- 12 million computers are thrown away each year in US (~10% are recycled now)

- 300-700 million computers will be obsolete in the US in the next few years

- The electronics and automobile industry are beginning to design for whole life of products
  - Source: National Safety Council

Photograph of discarded computers. Image removed for copyright reasons.
Problems with Electronics

- Designers are not responsible for end of life design

- Product manufacturing does not consider the entire lifetime of the product

- Result is *waste*
  - Economically inefficient
  - Environmentally harmful
  - Socially irresponsible

→ UNSUSTAINABLE
Buildings are Not Permanent

- Stone pinnacles of cathedrals are replaced ~200 years

- Buildings are waste in transit
Goals of Structural Design

- Efficiency
- Economy
- Elegance

The Tower and the Bridge: The New Art of Structural Engineering, by D.P. Billington
Goals of Structural Design

- Efficiency
- Economy
- Elegance

But all must consider the environmental impact as well
EFFICIENCY IS IMPORTANT: New materials in construction, such as wrought iron and steel, lead to greater concern for efficiency.
20th Century Design Concern

MAINTENANCE IS IMPORTANT: The initial design is important, though we must also design for maintenance throughout operating life

Photographs of bridges in need of repair.

Images removed for copyright reasons.
21st Century Design Concern

“END OF LIFE” IS IMPORTANT: Waste from the construction industry is a vast consumer of natural resources on a global scale.

Photographs of bridges being demolished.

Images removed for copyright reasons.
Design Matters

- 19th Century: Efficient use of materials
- 20th Century: Maintenance matters
- 21st Century: End of life matters
Case Study: Williamsburg Bridge

- Opened in 1903 as longest span in the world
- Designed with the elastic theory of suspension bridge design, which did not account for the stiffening effect of a cable
- Boasted to be the “strongest” suspension bridge at the time

Williamsburg Bridge, 1904
Williamsburg Bridge

- Regarded as the ugliest suspension bridge (doesn’t help that it is next to the stunning Brooklyn Bridge)

Brooklyn Bridge, 1883

Williamsburg Bridge, 1904
Williamsburg Bridge

- Carried traffic and trains throughout the 20th century
- But maintenance was neglected entirely for decades
- In 1988 the poor condition of the bridge became an emergency

Photographs of the bridge throughout the next several slides were removed for copyright reasons.

Williamsburg Bridge, 1937
Decay of Williamsburg Bridge

- Main cables were corroded badly (not galvanized)
- Pin joints in the main trusses were corroded
- Rusted girders

Williamsburg Bridge, 1980’s
Williamsburg Bridge Design Competition

Winning design by Jorg Schlaich, 1988
Estimated cost: $700 M
How to replace the Williamsburg Bridge?

- A vital link to Manhattan: the bridge could not be taken out of service

- Must use the same site: property for new approach spans is too expensive
Conclusion: Williamsburg Bridge Stays

At least 100 more years of service
1990-2005:
Rebuilding the Williamsburg Bridge

- New cables, new girders, new roadways, new bearings, new paint, etc…
- Cost approximately $1 billion; more than a new bridge
Williamsburg Bridge Rating

The Williamsburg Bridge is ranked as the most structurally deficient bridge in the USA carrying more than 50,000 cars per day.

Rebuilding the Williamsburg Bridge: Technical Problems

- How to replace main cables?
  - One strand bundle at a time

- How to replace deck while traffic flows?
  - Lightweight orthotropic steel deck placed at night

- How to protect river and traffic from lead paint on the bridge?
  - Contain large areas with plastic
Designing for Maintenance

- Develop a maintenance plan for your structure
- Design components which are accessible and replaceable
- Avoid toxic materials which are hazardous for future maintenance operations
‘Architects and engineers are the ones who deliver things to people’

- “We can only get there...if the key professionals who deliver things to people are fully engaged... [architects and engineers], not the politicians, are the ones who can ensure that sustainable development:
  - is operational
  - is made to work for people
  - delivers new ways of investing in our infrastructure, new ways of generating energy and providing a built environment
  - delivers new ways of using consumer durables.
  - There is no point along the sustainable development journey at which an engineer will not be involved.

  (address to RAE, June 2001)
CO$_2$ Emissions in the US

- US: 5% of world population, 25% of greenhouse gases

- UK: commitment to cut CO$_2$ emissions 60% by 2050 (well beyond the goals of the Kyoto Protocol)
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: ~33,000 lbs of CO$_2$/year/person (-7% from 1990)
- But individual contributions are only 1/3 of per capita contributions – rest is industry, agriculture, etc.
- So individual’s annual goal would be 11,000 lbs (though many scientists are calling for much greater reductions)
Kyoto Protocol and $\text{CO}_2$

- To meet Kyoto Protocol: $\sim 11,000$ lbs of $\text{CO}_2$/year/person (-7% from 1990)

- This is equivalent to:
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: $\sim$11,000 lbs of CO$_2$/year/person (-7% from 1990)

- This is equivalent to:

  2 coast to coast flights
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: $\sim$11,000 lbs of CO$_2$/year/person (-7% from 1990)

- This is equivalent to:

  Driving about 11,000 miles
Kyoto Protocol and $\text{CO}_2$

- To meet Kyoto Protocol: $\sim11,000$ lbs of $\text{CO}_2$/year/person (-7% from 1990)

- This is equivalent to:

16 cubic yards of concrete
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: ~11,000 lbs of CO$_2$/year/person (-7% from 1990)

- This is equivalent to:

  14 cubic feet of steel
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: $\sim$11,000 lbs of CO$_2$/year/person (-7% from 1990)

- This is equivalent to:

  5 cubic feet of aluminum
Kyoto Protocol and CO$_2$

- To meet Kyoto Protocol: ~11,000 lbs of CO$_2$/year/person (-7% from 1990)

- This is approximately equivalent to:
  - Fly coast to coast twice (economy class)
  - Drive 11,000 miles (20 mpg)
  - Use 16 yds$^3$ of concrete
  - Use 14 ft$^3$ of steel
  - Use 5 ft$^3$ of aluminum
Kyoto Protocol and CO$_2$

- Driving an SUV which gets 20 mpg:

- Using this material = driving this distance (approximately)
  - 1 yd$^3$ of concrete = 700 miles
  - 1 ft$^3$ of steel = 800 miles
  - 1 ft$^3$ of aluminum = 2200 miles
Kyoto Protocol

- Aims to reduce CO$_2$ emissions by 7% over 1990 levels (though the UK has just committed to going much further – 60% reductions of current emissions)

- Would limit personal carbon emissions to 11,000 pounds of CO$_2$/year

- This quantity of CO$_2$ is produced by:
  - Two coast-coast flights (economy class)
  - Driving 11,000 miles (with 20 mpg fuel efficiency)
  - Casting 16 cubic yards of concrete
  - About 14 cubic feet of structural steel
  - About 5 cubic feet of virgin aluminum
Kyoto Protocol

- Aims to reduce CO$_2$ emissions by 7% over 1990 levels (though the UK has just committed to going much further)

- This requires approximate CO$_2$ emissions of 33,000 lbs/year for each person in the US

- Only about 1/3 comes from personal decisions, the rest is due to industry and services

- **Architects and engineers contribute to the “industry and services”**
In the United States, buildings account for:

- 37% of total energy use
- (65% of electricity consumption)
- 30% of greenhouse gas emissions
- 30% of raw materials use
- 30% of waste output (136 million tons/year)
- 12% of potable water consumption

Source: US Green Building Council (2001)
Buildings: The real SUV’s

In the United States, buildings account for:

- 37% of total energy use (65% of electricity consumption)

- 30% of greenhouse gas emissions

Photographs of buildings at night.
Images removed for copyright reasons.
Coal is the Future of US Energy

Enough coal to meet US energy needs for ~200 years

Coal: $30/ton

True cost: ~$150/ton
## Energy and Buildings

<table>
<thead>
<tr>
<th>Need</th>
<th>Current Solution</th>
<th>Sustainable Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>Lights</td>
<td>Daylight</td>
</tr>
<tr>
<td>Heating</td>
<td>Power grid</td>
<td>Better insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Renewable energy</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air-conditioning</td>
<td>Natural ventilation</td>
</tr>
</tbody>
</table>

What is required?  → Better DESIGN
Embodied Energy and Operating Energy for Buildings

KEY
A = High operating
B = Normal operating
C = Low operating
D = Embodied

Figure by MIT OCW.
Typical Building Embodied Energy

Breakdown of Initial Embodied Energy by Typical Office Building Components Averaged Over Wood, Steel and Concrete Structures [Cole and Kernan, 1996].

Average Total Initial Embodied Energy 4.82 GJ/m²

Figure by MIT OCW.
## Range in Embodied Energy

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Low value</th>
<th>High value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural aggregates</td>
<td>1500</td>
<td>0.05</td>
<td>0.93</td>
</tr>
<tr>
<td>Cement</td>
<td>1500</td>
<td>6.5</td>
<td>11.7</td>
</tr>
<tr>
<td>Bricks</td>
<td>~1700</td>
<td>1.7</td>
<td>16</td>
</tr>
<tr>
<td>Timber (prepared softwood)</td>
<td>~500</td>
<td>0.26</td>
<td>3.6</td>
</tr>
<tr>
<td>Glass</td>
<td>2600</td>
<td>34</td>
<td>81</td>
</tr>
<tr>
<td>Steel (sections)</td>
<td>7800</td>
<td>190</td>
<td>460</td>
</tr>
<tr>
<td>Plaster</td>
<td>~1200</td>
<td>1.3</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Source: BRE, UK, 1994
Choosing Materials

- Environmental Impact
- Durability
- End of Life
Is concrete a green material?

- Concrete is made from local materials.

- Concrete can be made with recycled waste or industrial byproducts (fly ash, slag, glass, etc).

- Concrete offers significant energy savings over the lifetime of a building. Concrete’s high thermal mass moderates temperature swings by storing and releasing energy needed for heating and cooling.
## Energy Required for Concrete

<table>
<thead>
<tr>
<th>Component</th>
<th>Percent by weight</th>
<th>Energy %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>12%</td>
<td>92%</td>
</tr>
<tr>
<td>Sand</td>
<td>34%</td>
<td>2%</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>48%</td>
<td>6%</td>
</tr>
<tr>
<td>Water</td>
<td>6%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Each ton of cement produces ~ 1 ton of CO₂
Is steel a green material?

Image removed for copyright reasons.
Steel Recycling

2000 STEEL CONSTRUCTION RECYCLING

<table>
<thead>
<tr>
<th></th>
<th>Estimated Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Beams and Plates</td>
<td>95%</td>
</tr>
<tr>
<td>Reinforcement Bar and Others</td>
<td>47.5%</td>
</tr>
</tbody>
</table>

Figure by MIT OCW.
Environmental Advantages of Steel

- Lower weight reduces foundation requirements
- Highly recycled and can continue to be recycled indefinitely
- Durable, if protected from corrosion
- Can be salvaged for reuse
Energy Consumption for Steel

EU Steel Industry Energy Consumption per Tonne of Hot-rolled Steel
EU Steel Industry CO₂ Emission per Tonne of Hot-rolled Steel
(3-year moving averages)

Specific energy consumption
Specific CO₂ emission

Figure by MIT OCW.
Environmental Disadvantages of Steel

- Very high energy use, predominantly from fossil fuels → produces pollution
- Lightweight, so lower thermal mass compared to concrete → requires more insulation
- Is susceptible to corrosion
The Greenest of Them All?

Only one primary building material:

- comes from a renewable resource;
- cleans the air and water;
- utilizes nearly 100% of its resource for products;
- is the lowest in energy requirements;
- creates fewer air and water emissions; and is
- totally reusable, recyclable and biodegradable.

And it has been increasing in US net reserves since 1952, with growth exceeding harvest in the US by more than 30%.

-American Wood Council
Planting trees?

- A healthy tree stores about 13 pounds of CO$_2$ per year -- NOT MUCH!

- Would require nearly 3,000 trees per person to offset CO$_2$ emissions

- Specifying timber reduces CO$_2$ emissions compared to steel and concrete, but carbon sequestration is a small contribution to this reduction

- Main advantage is that wood does not produce nearly as much CO$_2$ as steel and concrete
High vs. Low Embodied Energy?

- Materials with the lowest embodied energy intensities, such as concrete, bricks and timber, are usually consumed in large quantities.

- Materials with high energy content such as stainless steel are often used in much smaller amounts.

- As a result, the greatest amount of embodied energy in a building can be either from low embodied energy materials such as concrete, or high embodied energy materials such as steel.
Embodied Energy per Stiffness

(kJ/MN-m)

Wood    Brick    Concrete    Steel
Steel and Concrete

- Energy intensive materials
- High associated CO₂ emissions
- Dominant structural materials
  - Industry standards
  - Many engineers have not designed with other materials
  - Economies of scale
  - Steel provides ductility, the ability to absorb energy before failing
- Many other materials can serve in place of steel and concrete
Spending on Construction

In industrialized nations, construction contributes more than 10% of the Gross Domestic Product (GDP)

An estimated 47% of total spending on construction is for renovation.

Source: Daratech (2001)
Construction Waste

- US Environmental Protection Agency (EPA) estimates 136 million tons of waste generated by construction each year

- Most from demolition or renovation and nearly half the weight is concrete

New construction: 8%
Renovation: 44%
Demolition: 48%
Reducing Waste

Design for Less Material Use
Use materials efficiently and maximize program use by combining spaces. (i.e., build smaller)

Design Building for Adaptability
Design multipurpose areas or flexible floor plans which can be adapted for use changes.

Recycle Construction Waste
Wood, metal, glass, cardboard etc. can be salvaged in the construction process. Materials should be used and ordered conservatively.
## Energy Savings from Recycling

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy required to produce from virgin material (million Btu/ton)</th>
<th>Energy saved by using recycled materials (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>250</td>
<td>95</td>
</tr>
<tr>
<td>Plastics</td>
<td>98</td>
<td>88</td>
</tr>
<tr>
<td>Newsprint</td>
<td>29.8</td>
<td>34</td>
</tr>
<tr>
<td>Corrugated Cardboard</td>
<td>26.5</td>
<td>24</td>
</tr>
<tr>
<td>Glass</td>
<td>15.6</td>
<td>5</td>
</tr>
</tbody>
</table>

Use Recycled Content Products and Materials

High recycled content:

Paper on both the face and the back of all drywall is a 100% recycled product.

Structural steel uses mostly recycled material (though it is still energy-intensive and responsible for harmful pollutants.)

Example of an item that you can specify:

Armstrong ceiling tiles contain 79% recycled material (cornstarch, newsprint, mineral wool, recycled tiles). Both the ceiling tiles and the suspension systems can also be reclaimed and recycled rather than dumped in a landfill.
Mineral fiber ceilings from renovation projects can now be efficiently reclaimed and reused through the Armstrong Ceilings Reclamation and Recycling Program.
Separating Waste

Photographs of construction waste (wood and concrete).

Images removed for copyright reasons.
Web site dedicated to Construction & Demolition waste minimization: onSITE

http://onsite.rmit.edu.au/

(Source of material for this lecture.)
Ecological Comparison of Materials

- Each material has environmental advantages and disadvantages

- Choice of material will depend on the site and design problem

- Embodied energy is only one of many considerations
Design Matters

● 19th Century: Efficient use of materials

● 20th Century: Maintenance matters

● 21st Century: End of life matters
Demolition: Lessons from History

- Sustainable structures must consider the “end of life” of the structure

- ~24% of solid landfill waste in the US is generated by the construction industry

- Up to 95% of construction waste is recyclable, and most is clean and unmixed

Source: 2002 Buildings Energy Databook
http://buildingsdatabook.eren.doe.gov/
Two Extreme Approaches to Sustainable Structures

1. **Permanence**: Very high quality construction, with materials which can be reused in future construction.

Designing for Permanence: The Roman Tradition

A series of photographs were removed for copyright reasons.

Pons Fabricius in Rome, 62 BC
Temporary Bridges: The Inca Tradition

Keshwachaka in Huinchiri, Peru
~1400 AD
Inca Bridge Construction: An Annual Festival

Day 1: Ropes made from local grass or plant fibers

Day 2: Old bridge is cut and new ropes are installed

Day 3: Roadway and handrails are added and bridge is complete
Grass Bridge Has Survived for 500 Years

- Maintenance plan is tied to the community
- Materials are locally available and environmentally sound
## Two Sustainable Bridge Types

<table>
<thead>
<tr>
<th>Inca suspension bridge</th>
<th>Roman arch bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>High stresses</td>
<td>Low stresses</td>
</tr>
<tr>
<td>High maintenance</td>
<td>Low maintenance</td>
</tr>
<tr>
<td>Short lifetime</td>
<td>Long lifetime</td>
</tr>
<tr>
<td>Low initial cost</td>
<td>High initial cost</td>
</tr>
<tr>
<td>Renewable materials</td>
<td>Reusable materials</td>
</tr>
<tr>
<td>Low load capacity</td>
<td>High load capacity</td>
</tr>
</tbody>
</table>
The Structure of the Future?

- Efficient: Materials are recycled, reusable, or low-energy

- Maintainable: Components can be replaced or improved or reused

- Adaptable: Can respond to changing needs and loads throughout its lifetime

Traversina Bridge, Jorg Conzett
Japanese Pavilion, Germany, 2000

- Recycled paper tubes
- Minimal foundations
- Recycled at end of the Expo
Stansted Airport Terminal

- Steel tubes can be disassembled
- Modular system for adaptation
- Can be recycled or reused at end of life
The Importance of History

- Case studies can illustrate successful and unsuccessful designs

- The designs of yesterday are the problems of today

- How do we design with the future in mind?
Design Questions to Consider

● In choosing structural system(s):

  – Flexibility of plan?
  – Can your building be adapted for alternative layouts?
  – Is the structural system economical?
  – Does it utilize local expertise?
  – How does the system help with natural lighting, natural ventilation, or thermal performance?
Design Questions to Consider

- In choosing materials:
  - What is the source for the materials?
  - What happens at the end of life of the materials?
  - Do the materials contribute to your other design goals? (transparency, thermal mass, etc.)

Photographs removed for copyright reasons.

Must consider site and building orientation to optimize daylight, ventilation, thermal insulation, etc.

www.bedzed.org.uk
Or you could treat architecture as sculpture...

Consideration of site and building orientation to optimize daylight, ventilation, thermal insulation, etc.???
Conclusion

In choosing a structural system and the materials for a building, consider:

1. CONSTRUCTION

2. OPERATION

3. DEMOLITION
‘Architects and engineers are the ones who deliver things to people’

“We can only get there...if the key professionals who deliver things to people are fully engaged... [architects and engineers], not the politicians, are the ones who can ensure that sustainable development:

- is operational
- is made to work for people
- delivers new ways of investing in our infrastructure, new ways of generating energy and providing a built environment
- delivers new ways of using consumer durables.

There is no point along the sustainable development journey at which an engineer will not be involved.

Royal Academy of Engineering, UK, June 2001
Sustainable design is good design

Global responsibility of engineers in the United States
Conclusions

- Each material has environmental advantages and disadvantages: good design is local
- Recycle or reuse materials to decrease waste
- Consider end of life in the initial design
- History suggests sustainable solutions: Inka structures (temporary) and Roman structures (permanent) can both be sustainable
Conclusions

- Construction industry generates enormous waste annually
- Individual designers can reduce this waste significantly
- Energy intensive materials like steel and concrete can be used more efficiently
- Alternative materials should be explored
Future Challenges

- Education of architects and engineers
  - Teaching design and analysis
  - Assessment of existing structures
  - Environment as a design constraint, not an opponent

- Maintenance and disposal plan for new structures

- Code improvements for the reuse of salvaged structures and new uses of traditional materials
Further Information

US Green Building Council:
www.usgbc.org

Department of Energy:
www.sustainable.doe.gov