Intelligent structural adaptability

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The average life of a building in Tokyo is six years. The average life of a building in the United States is thirty-one years. Buildings are typically replaced for reasons other than the building itself including high operational costs, increased density requirements, or new programmatic needs. Building structures are typically designed so efficiently that little or no upward expansion can be made without a change in the existing structure. Limited resources, climate change and new technology direct changes in design thinking and yet designers still structurally design for present conditions with little thought for resiliency or adaptability.

The environmental impact of renovation or replacement considers the material and operational attributes of a building; a method justifying its replacement in some cases. But, the material impact of designing for future expansion will always be less than demolition and replacement due to the simple fact that no matter the original size or replacement size, the difference between the two scenarios is the embodied energy in the original building plus that in demolition. The question therefore is why don't developers think ahead? The answer lies in either economics or the uncertainty of future use.

This paper posits that cities will become denser requiring continued addition of height to existing buildings. It investigates the environmental and economic impact of designing for longevity by comparing strategies for the design of structural systems for future expansion to the design of present conditions. This paper speculates on the structural impact of the development of new materials with higher allowable stresses and lighter densities as well as the impact of robotic construction.

KEYWORDS: Structural Resiliency, Embodied Energy, Structural Efficiencies

INTRODUCTION

Climate Change, population growth, cultural/social – lifestyle changes and limited global resources are all factors that indicate a need for resilient design. Between 1990 and 2013 there was a 34% increase in global warming effect caused by greenhouse gases.(WMO 2014). Between 2012 and 2013, the increase in Carbon Dioxide was the largest in thirty years. Carbon Dioxide currently accounts for about 65% of the radiative forcing by global greenhouse gases. Buildings contribute to the increase in carbon dioxide through the burning of fossil fuels for heat energy and through the manufacturing and processing of building materials. Therefore, from a structural point of view, it is in global best interest to reduce the embodied energy in construction materials and processes. Global warming is indicative of climate change. An increase in weather extremes is predicted including a change in cyclone patterns. *Climate Change 2007: The Physical Science Basis* (Meehl 2007, p.768) predicts cyclone patterns will move farther from the equator subjecting cities as far north as 40 degrees latitude to winds in excess of 150mph. Changes in wind speed indicate necessary changes in design loads for lateral force resistance.

The World Health Organization reports on their Global Health Observatory site that 54% of the population currently live in urban areas, and increase from 34% in 1960. The WHO predicts that urban populations will grow by 1.84% per year in the next 5 years, 1.63% per year between 2020 and 2025 and 1.44% between 2025 and 2030. (WHO 2014). The United Nations Department for Economic and Social Affairs/ Population Division's World Urbanization Prospects: The 2011 Revision (Heilig 2012) predicts a 75% increase in urban populations by 2050 with a rise from 3.63 to 6.35 billion people. Any increase in urban population will require an increase in urban density. Urban densification is already apparent with the destruction of structurally sound buildings to make way for taller projects. The Athena Institute conducted a three year study in Minneapolis/St. Paul (Athena 2004) and found that of the 227 structures demolished during the three and one half year period from 2000 to mid-2003, only 31% were demolished due to the physical condition of the building and 7% from fire damage, while 57% were demolished because of area redevelopment or because the structure was not suitable for anticipated use. Only one third of the demolished structures were made of concrete and steel, but of those, 63% of concrete structures and 80% of steel structures demolished were under 50 years old.

1.0 NOW OR AGAIN

1.1. The logic of planning ahead

Buildings are typically replaced for reasons other than the building itself including high operational costs, increased density requirements, or new programmatic needs. Yet developers generally do not plan for future use either for economic reasons or because of the uncertainty of future use. Developers rely on an economic argument for demolition and rebuild. Given the time value of money, is it better to spend additional money from the project budget on structural design for future expansion or design as efficiently as possible and demolish for rebuilding? Factors include the projected cost of limited resources in the future and the cost of waste disposal. There is an environmental argument for planning ahead. It ultimately saves resources. The environmental impact of renovation or replacement considers the material and operational attributes of a building; a method justifying its replacement in some cases. However, the material impact of designing for future expansion will always be less that of demolition and replacement. This is due to the simple fact that no matter the original size or replacement size of the structure, the difference between the planning ahead and demolition and replacement is the embodied energy in the original building structure plus that involved with demolition. Retrofitting is another factor that must be considered. Retrofitting keeps the initial building cost low and saves the financial and environmental cost of demolition, although it is not an easy task and not always cost effective. In order to determine the best approach to structural expansion, the possible strategies are defined based on designing structure for future expansion, demolition and rebuild, or retrofitting.

1.2. Possible expansion strategies:

The following options are the possible ways to approach future building expansion.

Option 1: Design for structural efficiency based on today's requirements for program and codes. This option would require the existing substructure and superstructure to be demolished and a new structure built when expansion is required.

Because the foundation of a building is the most difficult to replace or retrofit and therefore most expensive portion of the structure to remove or retrofit for additional levels, options 2 and 3 focus on the design of the foundation only for future expansion while the superstructure is designed for immediate programmatic needs. In the future, the superstructure would require either retrofitting or demolition. These options are advantageous in that the embedded energy in the foundation is not wasted and the expense of concrete removal, earthwork, formwork and new concrete placement is spared.

Option 2: Design the substructure for future expansion but demolish and rebuild the superstructure.

Option 3: Design the substructure for future expansion and retrofit the superstructure to meet expansion demands.

Options 4: A comprehensive future design strategy - Design the substructure and superstructure to support future loads consistent with projected increase in urban density for a given area. This option can be subdivided into two categories: one accommodating continued use of the building during expansion and the other requiring the building to be vacated during construction.

2.0 MATERIAL MATTERS

2.1. Material amounts

As an example for calculation purposes, an infill lot providing a building outline of 60ft by 120ft is divided into 9 bays 20ft by 40ft each. The floor to floor height is 12ft and the construction is A992 Structural Steel.

Based on a need for 75% more urban population in the next 50 years, the additional steel required in the initial stage of development to allow for the addition of 75% more levels in 50 years was calculated for initial heights of 4, 8,12, 16, and 20 levels. Only gravity loads (factored live and dead loads) were considered. Only about 40% of steel framing costs come from the actual material costs itself, and 1% from transportation (building.co.uk 2012). Further, estimating that structural costs in multi-residential projects are 15% (SteelConstruction.info 2012) of the total project costs with superstructure estimated at 10% and substructure estimated at 5%, yields an increase in project cost due to an increase in steel of only .1 (.41) = .041 times the additional steel percentage. The result of planning for 75% expansion adds less than 0.3%

additional steel cost to the project due to superstructure design.

If the superstructure is designed for additional levels, the substructure must also be designed for additional levels. Material cost of concrete in a concrete foundation system is estimated to be 50% of total foundation costs and foundation costs are estimated at 6% of total project costs. Given this, the increase in project cost due to planning the substructure structure for future expansion loads yields (percent concrete volume increase)(.5)(6%) = .03 times percent concrete volume increase.

Taken together, the increase in total project costs from 75% substructure and superstructure expansion planning is 4.7% or less for midrise structures. Using the same assumptions, designing for 100% expansion creates 5.2%, and a 200% expansion creates 10.7% or less additional total project cost. In every scenario with a mat foundation, the additional concrete required for planning ahead incurs over 93% of the additional project cost.

Table 1: Additional Project costs for Option 4 relative to Option 1 with Mat Foundations.

MAT FOUNDATION							
75% additional levels planned		STEEL STRUCTURE			CONCRETE STRUCTURE		
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 concrete	% Additional Project Cost	% add'l stage 1 columns	% add'l stage 1 ftg.s	% Add'l Project Cost
2.0	2.0	1.5	156.0	4.7	0.0	156.0	4.7
3.0	3.0	3.0	97.0	3.0	0.0	97.0	2.9
4.0	3.0	3.3	78.0	2.5	0.0	78.0	2.3
5.0	4.0	4.2	100.0	3.2	0.0	100.0	3.0
6.0	5.0	5.2	111.0	3.5	0.0	111.0	3.3
7.0	6.0	6.1	123.0	3.9	0.5	123.0	3.7
8.0	6.0	6.2	118.0	3.8	0.9	118.0	3.6
9.0	7.0	7.0	124.0	4.0	1.9	124.0	3.8
10.0	8.0	7.9	138.0	4.5	2.9	138.0	4.3
100% additional levels planned							
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 concrete	% Additional Project Cost	% add'l stage 1 columns	% add'l stage 1 piles	% Add'l Project Cost
2.0	2.0	1.5	156.0	4.7	0.0	156.0	4.7
3.0	3.0	3.0	97.0	3.0	0.0	97.0	2.9
4.0	4.0	4.4	109.0	3.5	0.0	109.0	3.3
5.0	5.0	5.2	121.0	3.8	0.0	121.0	3.6
6.0	6.0	6.2	144.0	4.6	0.3	144.0	4.3
7.0	7.0	7.1	157.0	5.0	1.1	157.0	4.8
8.0	8.0	8.0	164.0	5.2	2.2	164.0	5.1
9.0	9.0	8.9	163.0	5.3	3.3	163.0	5.1
200% additional levels planned							
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 concrete	% Additional Project Cost	% add'l stage 1 columns	% add'l stage 1 piles	% Add'l Project Cost
2.0	4.0	4.2	282.0	8.6	0.0	282.0	8.5
3.0	6.0	6.1	225.0	7.0	0.0	225.0	6.8
4.0	8.0	11.4	264.0	8.4	0.5	264.0	8.0
5.0	10.0	10.3	303.0	9.5	2.3	303.0	9.2
6.0	12.0	12.0	335.0	10.5	4.6	335.0	10.3

Not every urban structure will be replaced or expanded to new heights in order to accommodate a 75% increase in urban density. Urban areas with low to mid-rise structures are most likely to see densification. With that in mind, I posit a scenario in which urban buildings with two to four levels will be replaced or expanded to four times their original height. Foundations for low rise structures may consist of individual footings but as the number of levels rises, individual footings no longer are practical and should be replaced by piles. This is because the required width of the footing becomes exceedingly large, especially with low soil bearing capacity. Even with a soil bearing capacity of 5000psf, the building scenario studied would be limited to 18 levels using a shallow foundation.

If friction piles are used in place of a mat foundation, increased project costs are greatly reduced, dropping from 4.7% to 1.1% for a planned expansion of 75%; 5.2% to 1.3% for 100% expansion planned; and 10.7% to 2.4% for 200% expansion planned.

Table 2: Additional Project costs for Option 4 relative to Option 1 with Driven Pile Foundations.

DRIVEN PILE FOUNDATION								
75% additional levels planned		STEEL STRUCTURE			CONCRETE STRUCTURE		
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 pile steel	% Add'l Project Cost	% add'l stage 1 columns	% add'l stage 1 piles	% Add'l Project Cost
2.0	2.0	1.5	41.5	1.1	0.0	47.9	1.4
3.0	3.0	3.0	41.5	1.1	0.0	45.5	1.4
4.0	3.0	3.3	32.3	0.9	0.0	34.7	1.0
5.0	4.0	4.2	34.2	1.0	0.0	36.1	1.1
6.0	5.0	5.2	35.4	1.1	0.0	37.1	1.1
7.0	6.0	6.1	36.3	1.1	0.5	37.7	1.2
8.0	6.0	6.2	32.3	1.0	0.9	33.4	1.1
9.0	7.0	7.0	33.4	1.1	1.9	34.4	1.1
10.0	8.0	7.9	34.2	1.1	2.9	35.1	1.2
100% additional levels planned							
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 pile steel	% Add'l Project Cost	% add'l stage 1 columns	% add'l stage 1 piles	% Add'l Project Cost
2.0	2.0	1.5	41.5	1.1	0.0	47.9	1.4
3.0	3.0	3.0	41.5	1.1	0.0	45.5	1.4
4.0	4.0	4.4	41.5	1.2	0.0	44.4	1.3
5.0	5.0	5.2	41.5	1.2	0.0	43.7	1.3
6.0	6.0	6.2	41.5	1.3	0.3	43.3	1.3
7.0	7.0	7.1	41.5	1.3	1.1	43.1	1.4
8.0	8.0	8.0	41.5	1.3	2.2	42.8	1.4
9.0	9.0	8.9	41.4	1.4	3.3	42.7	1.5
200% additional levels planned							
Stage 1 number of levels	Stage 2 Add'l levels	% add'l stage 1 steel	% add'l stage 1 pile steel	% Add'l Project Cost	% add'l stage 1 columns	% add'l stage 1 piles	% Add'l Project Cost
2.0	4.0	4.2	73.4	1.9	0.0	83.7	2.5
3.0	6.0	6.1	73.3	2.0	0.0	79.8	2.4
4.0	8.0	11.4	73.3	2.2	0.5	78.0	2.4
5.0	10.0	10.3	73.3	2.2	2.3	77.0	2.4
6.0	12.0	12.0	73.3	2.3	4.6	76.3	2.6

2.2. Material types

Not all buildings are constructed of steel. An identical column grid and floor-to-floor height constructed of concrete yields different results. Given the design criteria of a slenderness ratio less than 22 for short concrete columns and an unbraced length of 12ft, the minimum width for a square column would be 22.67”. This number would be rounded up to 24”. This means that for future building expansion to a total of 11 levels or less, the only additional initial cost to the superstructure would be the amount of rebar in the columns. The total impact on project cost from additional column concrete would be .5(.12)(percentage increase in concrete volume). Using mat foundations, the change in Project Cost due to planning for expansion in concrete construction is only 0.3% greater than with steel construction.

It should be noted that while the examples listed are structures steel and concrete structures, most multifamily housing in the United States four levels or less has western frame construction. Western frame buildings cannot be expanded with additional levels due to code restrictions and therefore must be demolished if expansion is desired. Since the only option for western frame construction is Option 1 or Option 2: discussion of this type using western framing must be considered for economic reasons, named Option 1A and Option 2A.

3.0 MONEY MATTERS

3.1. The time-value of money for the next 50 years.

The Federal Government targets a 2% annual inflation rate, although that number is seldom met. The average in the past fifty years is 4.48%. With some annual inflation rate (i), the cost of project construction in fifty years would be today's project cost times $(1+i)^{50}$; meaning that at 2% annual inflation, the same project cost in fifty years would cost $1.02^{50} = 2.69$ times the cost today.

Using assumptions of $250/sf for construction, $200/sf for retrofitting, and $100/sf for demolition and an annual inflation rate of 2%, the costs in 2065 would be $673/sf for construction, $538/sf for retrofitting and $269/sf for demolition. The following results were obtained:

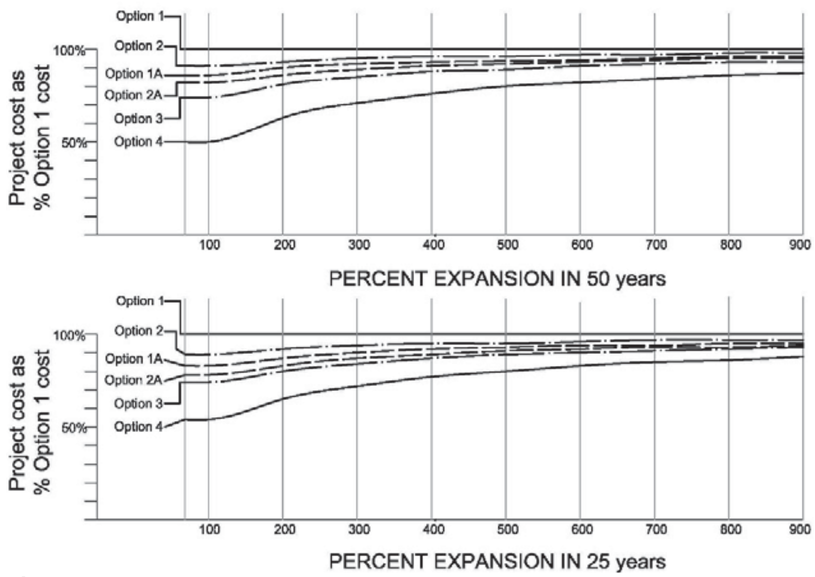

Figure 1: Comparison of project costs for all Options as a percentage of Option 1.

As mentioned previously, most multifamily housing in the United States having four levels or less is western frame construction. Four-level western framing cannot be expanded due to code restrictions and therefore must be demolished if expansion is desired (Option 1). Not only is western framing inexpensive to build; demolition is efficient and inexpensive compared to steel or concrete structures. In consideration of this, a construction and demolition rate for Stage 1 western construction was given at 50% of the costs listed above for Option 1A and Option 2A.

Regardless of the amount of planned expansion, *Option 4: Design both substructure and superstructure for future expansion* is the most economical choice, followed by Option 3, Option 2A, Option 1A, Option 2 and finally Option 1. Options 1 and 2 plan for demolition of the stage one steel superstructure, whereas Options 1A and 2A plan for demolition of a western frame superstructure.

Another consideration is the fact that demand may allow a developer to expand before fifty years. A change in the number of years before expansion has no effect on the order of efficiency of the expansion Options and very little change on the actual efficiency relative to Option 1.

The problem with predicting future rates is that no one can really predict the future. If waste disposal costs skyrocket, so will demolition costs. If steel prices drop or construction costs plummet due to affordable robotic construction methods, construction and renovation costs will vary. If material shortages occur, alternate materials will become prevalent. If alternate materials are used, new building technologies will develop. If climate change continues unchecked, higher lateral forces and greater thermal expansion will change structural design. Given these uncertainties, the analysis was run again using 50% of former demolition and retrofitting rates. The results remain the same. If inflation rates change from the Federal goal of 2%, even as little as 1%, then the savings value of Option 4 will inversely change by about 3%.

3.2. Building occupancy during expansion

Building occupancy during expansion can only occur in Option 4 where no structural demolition or retrofit is required and possibly in Option 3 where superstructure retrofit is required and partial occupancy may occur. Occupying all or part of a building during expansion presents a number of problems. Building Access to occupants and workers need to be defined for safety and security reasons. If freight elevators are limited to expansion construction use, it precludes or impedes the moving of large items by occupants, trash removal and the like. Acoustic comfort is a major concern. Structure-borne sound, especially during steel modification, intensifies the noise distraction caused by construction. Ventilation and cooling equipment located on the roof needs to be relocated or replaced and other MEP systems will require temporary shut off points. The only advantage to occupying a building during expansion is monetary and this advantage only occurs if the additional cost of construction is outweighed by the lease income revenue.

4.0 EMBODIED ENERGY

Using the Hammond & Jones Embodied Energy rating for materials (Hammond & Jones 2008), the embodied energy in the production of structural concrete is 1.11MJ/kg and for structural steel with 42.3% recycled content, 24.40 MJ/kg. For demolition, energy rates are 0.301MJ/kg for steel and 0.107 MJ/kg for concrete. Steel has a high value and is easily reused or recycled. Concrete can be recycled, but at a higher cost and typically only about 73% of concrete is reclaimed as recycled (Athena 1997). A comparison of Options 1 and 4 for embodied energy reveals, as expected that the embodied energy in Option 4 is about 2/3 that of Option 1 for 75% expansion, but that as the rate of expansion increases, the difference in embodied energy for both stages between the two options decreases.

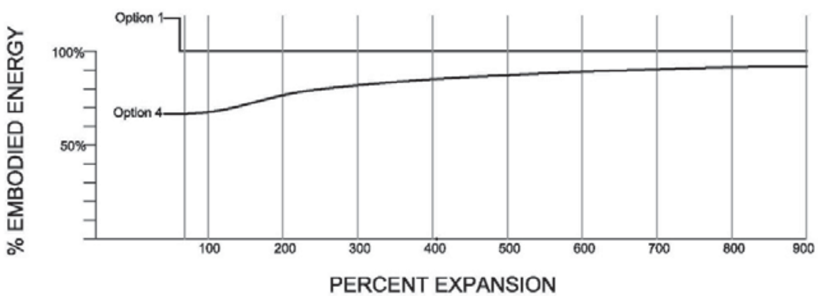

Figure 2: Embodied energy for Option 4 relative as a percentage of Option 1.

5.0 NICOMACHEAN ETHICS

Cowee and Schwehr (Cowee 2012) liken adaptability to Aristole's *Nicomachean Ethics* stating avoidance of excess at either end of the spectrum will produce the best model for sustainable and economic balance. A true nicohmachean balance would require a monetary value for embodied energy in order to compare the differences between options for economics and sustainability combined. Using Option 1: Build – demo-build as a baselin, Option 4: Build for expansion can be compared. The current average rate of electricity in the United States is about 0.12$/kWH. This number converts to 0.00341$/MBTU.

Factoring in Embodied energy costs does not significantly change the cost ratio between Option 1 and Option 4. Even an increase over 4000% in energy costs, raising the rate from .12$/kwH to 5.0$/kwH, still does not create a large enough shift to consider Option 1. The economical and sustainable choice is Option 4: Design both Foundation and Superstructure for eventual expansion.

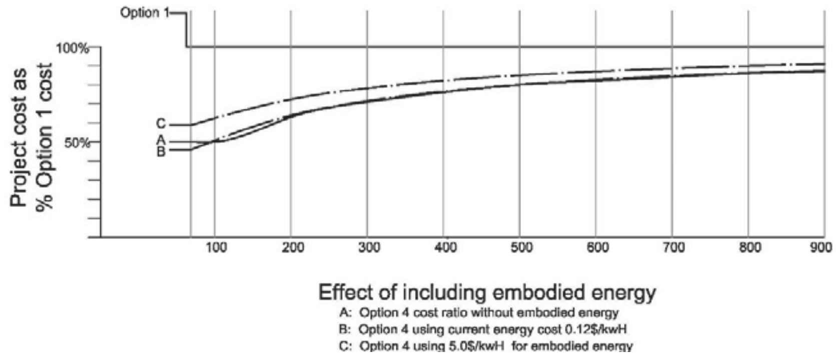

Figure 3: Comparison of Option 4 project costs using a dollar value for embodied energy cost.

The question becomes, if designing structure for future expansion is the best choice for both economics and sustainability, then why don't developers do it? The answer probably lies in the initial cost despite the project cost difference being less than 3%. 3% of a ten million dollar project is $300,000. That amount does not include the cost of financing the $300,000. It would seem the only motivation for a developer to spend the extra money up front is if he/she plans to retain the property and eventually expand it. The property would be more valuable if no demolition is be required for expansion, but only if the existing structure is suitable for future design.

6.0 FLEXIBILITY

Stewart Brand's layer diagram from *How Buildings Learn* (Brand 1995) is meant to illustrate the changing nature of buildings as a result of differences in the longevity of its systems and components. Brand sees the structure of a building as the most permanent layer second only to site, which is how designers traditionally viewed structure: permanent and unchanging. This is a logical view given the cost of changing structural systems to adapt to new uses.

6.1. Unitization

Recently, there has been a surge of interest in transitory or "pop-up" structures and in prefabricated structural units that imply a flexibility. For prefabricated units that are infilled into an existing structure, the structure is designed to carry loads resulting from being fully loaded with units. For prefabrication that relies on the stacking of units, every unit must be over-designed in order to support the number of units that could possibly be placed atop it. Although schematically and financially there is much flexibility, structurally unitization is not inherently efficient. A module 20' by 20' by 12' high designed for stacking would use about 75% more steel than the steel structure of an equivalent height as described for earlier analyses. The total project cost would increase due to the amount of steel used and cost of module transportation and lifting, but decrease due to the efficiencies of prefabrication such as building under controlled conditions with higher levels of automation and incurring less on-site time.

6.2. Change of use

In one sense, the permanent nature of structure reinforces the idea of planning ahead. However, there are scenarios in planning for expansion where the structure of existing levels may change significantly. For example, if a site is designed to house a large open space for several years before building a residential tower atop, the stage 1 structural system could have perimeter walls supporting a space frame. The space frame would be removed and additional columns placed to support the stage 2 tower. This scenario is neither static nor flexible and suggests that structural planning for future expansion be limited to cases where stage 1 and stage 2 uses employ the same structural system type.

Another consideration is the development of new and better structural materials. Grade 5 Annealed Titanium (Ti6Al4V) has a compressive yield strength of 125ksi compared to A995 Steel at 50ksi. Logic dictates titanium design would use 50/125 = 40% the volume of steel, which seems to be more efficient. Titanium density is 56% that of steel but costs 10 times as much. Given this, the cost of a titanium structure would be 0.4(0.56)(10) = 2.24 times the equivalent in steel. What's worse, the embodied energy per pound of Titanium is 16.4 times that of steel meaning a Titanium structure has (0.40)(.56)(16.4) = 3.67 times the embodied energy of the equivalent in steel. Should processing methods change reduce embodied energy and cost, Titanium could become a staple in the building industry.

Laminated Bamboo has a compressive yield strength of 13.5ksi compared to A995 Steel at 50ksi. Logic dictates titanium design would use 50/13.5 = 370% the volume of steel. Laminated Bamboo weighs 9.8% the weight of steel and costs 4.15 times as much. Given this, the cost of a laminated bamboo structure would be 3.7(0.098)(4.15) = 1.5 times the equivalent in steel. However, the embodied energy per pound of Laminated Bamboo production is about the same as steel meaning a Laminated Bamboo structure has (3.7)(.098)(1) = 0.36 times the embodied energy of the equivalent in steel. This is a case where a reduction in price and a change in building codes could trigger more use of Laminated Bamboo structures. Still, the impact on expansion would be minimal because although the weight of the structure is reduced, the other dead loads and the live loads will remain the same.

7.0 DESIGN LIMITATIONS

It is concluded that structural planning for future expansion is the economic and sustainable choice if the existing structure is suitable for the expanded use. This logic acknowledges the design limitations imposed on the stage 2 designer. That said, it must also be acknowledged that both client and designer may find the existing structure unsuitable for the vision of the next building use. This is not necessarily an arbitrary aesthetic choice. The change in design strategies, building construction and consumer values are constantly changing. The last two big changes in structural design were the development of steel frame systems to allow curtain wall construction and the development of computer-aided design to allow complex shape analysis and fabrication. To assume that there will not be another big change in the next fifty years would be naïve. Yet, a survey of the structural types employed today shows most buildings employ a beam and column system of steel and/or concrete in fairly orthogonal form. This does not mean that future expansion must follow suit; it is the challenges of limitations that brings ingenuity to the design process.

REFERENCES:

Athena Institute, 2004. *Minnesota Demolition Survey: Phase Two Report*.

Athena Sustainable Materials Institute, 1997. Demolition Energy Analysis of Office Building Structural Materials, Ottawa, Canada.

Brand, Stewart, 1995. *How Buildings Learn: What Happens After They're Built*, Penguin Books.

Building.co.uk, 2012. Steel insight: Cost Planning through design stages, http://www.building.co.uk/steel-insight-cost-planning-through-design-stages/5034975.article

Cowee, Natalie and Peter Schwehr, 2012. *The Typology of Adaptability in Building Construction*, VDF Hochschulverlag.

Hammond, G.P. & Jones, C.L., 2008. *Embodied Energy and Carbon in construction material*s, Proceedings of the Institution of Civil Engineers, Energy, 161 (2): 87-98.

Heilig, Gerhard, 2012. *World Urbanization Prospects: The 2011 Revision*, United Nations, Department of Economic and Social Affairs.

Meehl, Gerald, T. Stocker, 2007, *Climate Change 2007: The Physical Science Basis*, ch.10, Cambridge University Press, Cambridge, UK and New York NY, USA.

WMO Greenhouse Gas Bulletin, No.10/ 9 September 2014, World Meteorological Organization

WHO Global Health Observatory, 2014 http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/