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Embodied Carbon and the Case for Longevity

隐含碳排放和建筑寿命

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Abstract

This paper explores the sustainability and longevity of today's residential building construction. It makes the case for 100-year design criteria for building frames and enclosure systems. Embodied carbon as a metric for making decisions and areas where residential building designs can be improved for longevity are highlighted.

Keywords: Longevity, Embodied Carbon, Service Life, Performance Objectives, Seismic, Wind

摘要

这篇论文将探讨当今住宅建筑的可持续性和使用寿命。它将以100年设计标准的建筑结构和外围系统为例。（文章）重点讨论了如何运用隐含碳度量值来确定住宅建筑的位置，从而提高建筑使用寿命。

关键词：使用寿命，隐含碳，使用期限，实施目标，地震，风

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Are buildings currently designed to a sustainable standard of longevity? The 2009 U.S. Census Bureau's American Housing Survey reports the median U.S. residence is 35 years old, built in 1974 (U.S. Census Bureau, 2009). In the retail industry, 25 years is frequently used for assessing a project's viability before major renovation or replacement. For sporting venues, it is also 25 years. These durations do not always define a building's lifespan, but they are significant to decision-making processes and the quality of developments built. As this relates to building infrastructure, are smart choices being made, and would these timelines change if higher-quality, more thoughtfully placed buildings were built?

Certainly not all buildings or building programs require the same longevity, but if societies are to remain vibrant and healthy, with attempts made to reduce carbon footprints within the built environment, careful consideration must be given to today's standard of building longevity.

This topic certainly engages a host of societal and economic issues, most notably land-use planning, growth management, and collective perspectives on what the future should look like for future generations. These issues go far beyond the insight brought by just one

当今的建筑设计符合使用寿命的可持续性标准么？ 2009年，美国人口普查局的美国住房调查显示美国建于1974年的住宅寿命中位数是35年（美国人口普查局2009年）。对于零售业房屋，在大型翻新或改建之前，估算一个项目的使用寿命通常是25年。对于体育场馆的使用寿命也是25年。 然而这些年限不能完全限定一个建筑的使用寿命。由于这关系到建筑物的基础设施，它们对于决策过程和开发建造质量具有深远的意义。我们的决策是否明智？如果所建造的建筑物质量更高、布局更合理，这些时间表是否可以改变？

当然，不是所有建筑物或建筑方案都要求有相同的使用寿命，但是如果社会要保持活力和健康，我们必须慎重考虑当今的建筑使用寿命标准，并试图减少建造环境中的碳排量。

这个话题牵涉到一系列的社会和经济问题，最明显的是土地规划、增长管理以及给予孙后代留下怎样的未来的公众观点。这些问题远远超出了一名工程师的洞察能力，但也许这也是这个话题的一部分--没有一个人可以给出所有的答案，对于我们能够做什么和应该做什么，当然每个人会持不同的观点。

一个结构工程师能给这个讨论所带来的是工具，用来告知大家我们今天对于建筑类

engineer, but perhaps that is also part of the issue. No one individual is going to have all of the answers, and certainly not everyone is going to share the same opinions on what can and should be done.

What a structural engineer can bring to this discussion are tools to inform the decisions we are making today—on building types and the longevity built into these projects—and how they affect long-term durability. This includes resistance to the natural hazards of wind and earthquakes. Longevity, however, also needs to include a discussion of water, mold, corrosion, and adaptability to future uses.

When looking at these issues, it must also be done through a lens of sustainability and minimizing impacts on the planet. Today's population is 7 billion people, projected to reach 9 billion by 2050. That is not far away, and as developing countries grow, there are lessons to learn, both good and bad, from historical U.S. zoning and building models.

The following discussion will focus on residential construction as a case study, but the message and implications of building to a higher quality and longer lifespan are applicable to most building types.

Carbon as a Decision-Making Metric

Carbon, like money, is a tool we can use for making informed decisions. Next to water, it is certainly one of the sustainability metrics receiving the most attention.

The Architecture 2030 Material Challenge (EIA, 2011) has insightfully highlighted that for traditional residential construction in the United States, it takes approximately 15 years of building operations before the operational carbon of energy surpasses the embodied carbon to construct (see Figure 1). For locations where operating energy/carbon footprints are low due to hydropower, nuclear, or renewable energy sources, this time frame can extend significantly. Either way, what this clearly shows is that it can be a mistake to focus on only energy. Short-lifespan developments, especially considering the infrastructure requirements that go into and around them, can be some of the most unsustainable construction created, regardless of whether a carbon-neutral energy use is achieved for the building.

Clarifying a project's embodied carbon is much harder than operational energy/carbon, which to date has defined building carbon discussions (Carbon Leadership Forum, 2011). Nor is operational energy/carbon accounting, where specific quantities of energy are measured through meters, the right framework for embodied carbon discussions. There is no embodied carbon meter to collect comprehensive data to make such an evaluation.

Taking a page from macro-economics, the embodied-carbon focus should not be on attaining absolute carbon numbers. More and better data is needed, but if the goal is to use this metric for making more informed choices, one should instead look at trends and comparative data. Using the science of statistics, many tools are available to analyze comparative data with enough relevance to be making decisions without looking at absolutes.

How does this embodied carbon input relate to building longevity? For one, double-bottom-line evaluations should be made, which look at the financial and carbon impacts of decisions together, and to the same timeline criteria. With this approach, like money, amortization of initial carbon impacts can be spread over a longer duration, so they represent a smaller portion of a development's overall carbon footprint. This is especially beneficial after factoring in not just the building frame but everything else that goes into its infrastructure development.

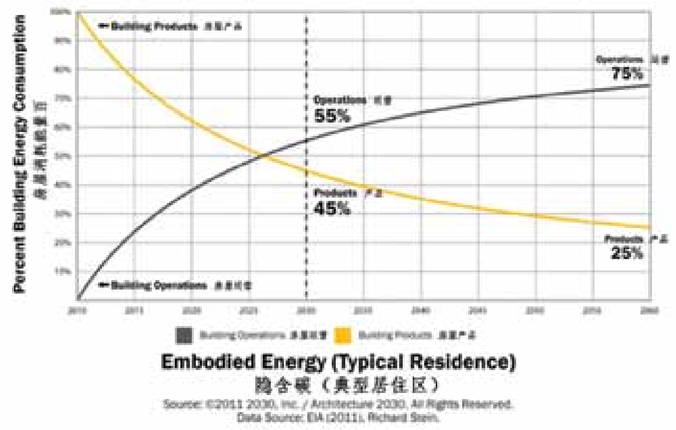

Figure 1. Architecture 2030 Material Challenge - Case Study Comparing Embodied and Operational Carbon Impacts Over Time. (source: 2030 Inc./Architecture 2030)
图1. 2030年建筑材料挑战 – 案例学习，随着时间的变化隐含碳量和运营碳量对比（出处：2030有限公司/建筑2030）

型和项目的使用寿命所作的决定以及这些决定如何影响建筑的长期持久性。这包括建筑物（如何）抵抗风和地震等自然灾害。然而，建筑使用寿命也需要考虑水、发霉、腐蚀和对未来用途的适应性这些要素。

(我们)还必须从可持续发展和最大限度减少对地球的影响这一视角来看待这些问题。当今世界人口是70亿，预计到2050年将达到90亿，这并不遥远。随着发展中国家的发展，它们可以从美国历史的区域规划和建筑模型中汲取到一些经验教训。

以下将集中以住宅建筑施工作为案例进行讨论，但是其中涉及的提高建筑使用寿命和建筑质量的信息和含义适用于大多数建筑类型。

碳是进行决策的一个度量标准

碳，就像钱一样，是一个我们可以用来进行决策的工具。它仅次于水，无疑是最能引起关注的可持续发展的衡量标准之一。

《2030年建筑材料的挑战》（美国能源信息管理局，2011）中强调，对于美国传统的住宅建造来说，房屋建筑需要大约运营15年后，其运营所需的碳能量才会超过在建造时所需的隐含碳能量（见图1）。如果建筑物位于水利、核能或其他可再生能源的附近而使其所需的运营能源/碳能量降低的话，则这个时间会大大延长。不管怎样，有一点可以明确的是，仅仅关注能源是错误的。特别是在考虑到连到其内部和周围的基础设施需求时，短寿命住宅小区开发所建的房屋可能是一些最不可持续发展的建筑物，无论这些建筑是否采用碳中性能源。

（虽然）迄今为止建筑碳研究中已经对运营能量/碳能做出了定义（碳领袖论坛，2011），（但是）对隐含碳的定义则要困难得多。能够用仪表测量具体的运营能量/碳能也不能为隐含碳的计量提供正确的框架。目前还没有隐含碳测量仪表可以收集全面的数据来做出评估。

从宏观经济学中得到的经验来看，对内含碳的关注不应集中在获取碳含量的绝对数值，而是需要获取更多更好的数据，但是如果目的是用这个度量标准来作出更明智的选择，那么应该通过看清趋势和比较数据来替代。利用统计学知识，在不需要关注绝对数值得情况下，有许多工具都可以用来分析足够关联的比较数据来进行决策。

隐含碳的输入如何与建筑寿命取得关联呢？其一，应当做在同等时间范围内共同考虑成本和碳对决策的影响的双底线评估。用这

Embodied carbon can be a very useful factor in double-bottom-line analyses of building choices. Such analyses should be kept statistically relevant but simple, and, if appropriate, include the carbon equivalent of resale value at the time boundary of the evaluation process.

100-Year Service Life

Today, many building economic decisions are made through a 15-, 30-, or 50-year lens, tied to construction financing loans. These timelines are important, but longer time periods should be considered. How do decisions change when the mindset is 100 years or more? Taking a longer-term view is not always easy, but it also is not as hard or expensive as many think. Certainly, many institutions already do this: university campuses and hospitals often have 100-plus-year outlooks for building decisions. In Europe and certain parts of Asia, 100 years may sound trite.

Certainly not all building inventory should be based on a 100-plus-year design life, but if the goal is to build an urban core that does not degrade faster than the population grows, a 100-plus-year mindset for residential buildings is an important step. Where buildings are built is most critical, but decisions on how they are built and potential long-term adaptability should at least consider 100-year implications.

As an analogy, consider which U.S. building is more desirable today: a 1960 or 1970 apartment building that is on its last legs and should probably be demolished or a 1910 or 1920 apartment building that carries historical charm and merits another renovation? One was built with longevity in mind. The other has a 50-year or less planned obsolescence, a term that came into vogue in the 1960s and 70s.

Building Performance Objectives

Current U.S. and international building codes follow earthquake and wind criteria specified in ASCE 7-10 (see Figures 2 and 3) (ASCE, 2011). For ordinary buildings, Risk-Targeted Maximum Considered Earthquake (MCER) demands are determined with the objective of providing a 1% in 50 year collapse risk. For the majority of the U.S., this corresponds to approximately a 2,000-year event. A "design earthquake" is then defined as 2/3 of these MCER demands and, on average, has a 10% probability of exceedence in 50 years (475-year mean recurrence interval). The data scatter that goes into these probability calculations varies this design earthquake recurrence from 200 to 800 years.

For wind, the criterion is a 700-year return period based on a single element in the structural system reaching its limit state, which is roughly targeted at a 10% probability of exceedence in 50 years.

In the above instances, these primary structural frame design criteria all include a 50 year point of reference for probability hazard discussions, which are then mapped out and placed within current building code documents.

Seismically, many will argue that thoughtfully designed building structures that follow current International Building Code design criteria and avoid system irregularities are performing well. Building structural damage from recent earthquakes in new construction meeting these criteria has been repairable in all but a few cases. The worst earthquake damage today typically involves building vulnerabilities in older buildings or buildings that do not meet these or similarly equivalent standards.

For 100-year longevity, changing our current design-basis earthquake criteria for the structural building frame may not be warranted.

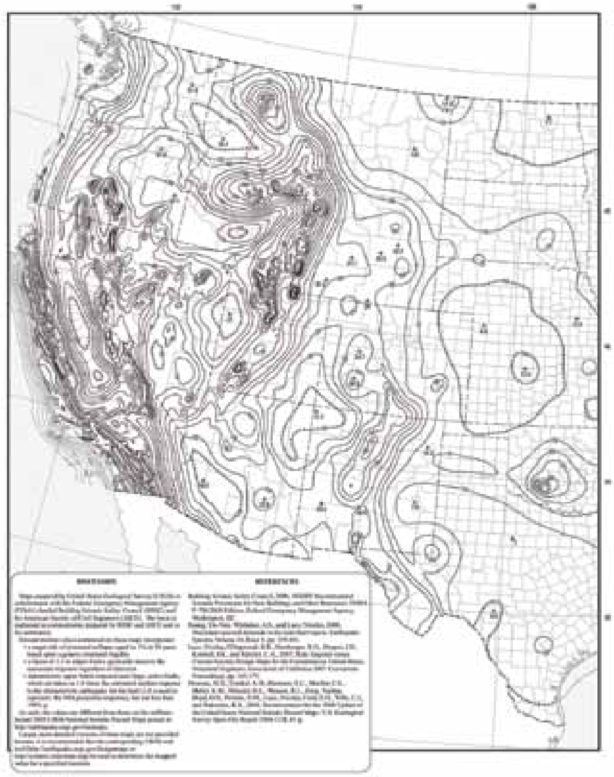

Figure 2. Seismic Design Criteria – Western U.S. (ASCE 7-10) (source: American Society of Civil Engineers)
图2. 抗震设计标准- 美国西部（ASCE 7-10）（出处：美国土木工程师协会）

种方法，初期的排碳量带来的影响可以在更长的时间范围内像钱一样实现“分期偿还”，故而降低在小区总排碳量中所占的比例。这样带来的益处不仅仅影响建筑结构本身，也影响着与小区相连的一切基础设施。

隐含碳在建筑选型双底线分析中是一个非常有用的因素。这样的分析应该保持统计相关，并且简单，如果可以的话，还应该包括在评估过程的时间界限中与转售价置相等的含碳量。

100年的使用期限

如今，许多建筑的经济决策长达15年、30年甚至50年，并与建设融资贷款息息相关。

这些时间线非常重要，但是应当考虑更长的时间周期。当设计使用年限更倾向于100年或更久的时候，如何改变当初的决定呢？从更长远的的角度来看待问题往往不容易，但也并不是像许多人所想的那样困难或昂贵。确实，许多机构已经开始这样做了：大学校园和医院的建设规划通常都超过100年。在欧洲和一些亚洲地区，100年可能听起来有些老套。

当然不是所有建筑寿命都应该基于100年以上的设计年限，但是如果目标是打造一个核心城市，并且其降级速度低于人口的增长，那么为住宅建筑树立一个使用期限在100年以上的理念是非常重要的一步。建筑物建在哪里是非常重要的，但是决定它们如何建造也同样重要，并且其潜在的长期适应性也应该至少考虑100年的影响。

打个比方，想一想在美国，下面所列的哪一栋建筑更令人向往：是一栋建于1960年或1970年马上就会被淘汰或被拆除的公寓大楼，还是一栋建于1910年或1920年承载着历史的轨迹且值得翻新的公寓大楼呢？一栋在建造的时候就考虑延长其使用寿命。而另一栋只考虑使用它50年甚至更短，并且随时准备废弃（一个在20世纪60、70年代开始流行的短语）。

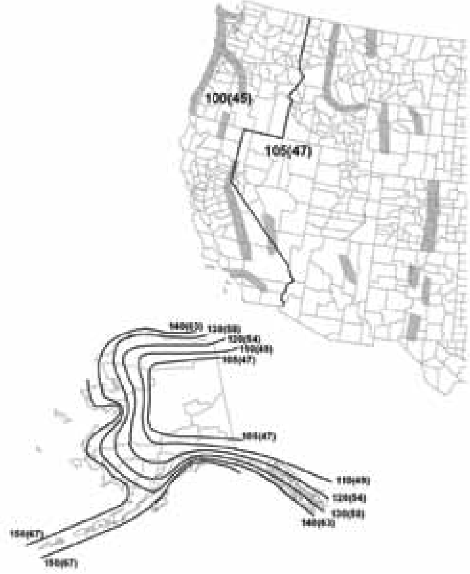

Figure 3. Wind Design Criteria – Western U.S. (ASCE 7-10) (source: American Society of Civil Engineers)
图3. 抗风设计标准- 美国西部（ASCE 7-10）（出处：美国土木工程师协会）

Changing the terminologies, however, to start thinking in a 100-year mindset could be significant for the discussions of cladding and other secondary systems. A 2% probability in 100 years is approximately the same 2,000-year mean return period event as a 1% probability in 50 years.'

An ongoing movement in seismic design is for future building codes to adopt more Performance-Based Design (PBD) approaches and envelop the analysis of more than one discrete level of ground shaking (San Francisco Building Department, 2008; PEER, 2010). In addition to the 1% in 50-year MCER event, while not code mandated, we now frequently consider a low-level serviceability event as well. Today, serviceability usually involves 50% probability of exceedence in 30 years (a 43-year event) with an objective of essentially elastic behavior for the structural frame. This second level of analysis is now also a topic for nonstructural building systems relative to both damage limitation and reparability within the life of the structural frame.

Since building contents will change and adapt over time, maintaining the 50% probability in 30-year serviceability event and redefining our MCER event in terms of 2% probability in 100 years would achieve appropriate frames of reference. This considers both the near-term hazard and the desired mind-set for discussions on durability of the building frame and its most essential components, such as the exterior enclosure system, relative to longevity potential.

Improving Building Longevity

Longevity in Earthquakes

Approximately 70% of earthquake losses are due not to collapse but damage to nonstructural cladding and building contents. Where do these nonstructural elements pose the most problems? For one, jointing of cladding for movement, especially at corners, is often poorly executed in the design and construction process. Projects with engineered curtain walls, such as high-rise commercial towers, typically have thoughtfully engineered exteriors. Unfortunately, for a wide collection of residential buildings, the exteriors often involve minimum engineering design input and a set of typical details, at best. Frequently, there is a lack of understanding of the engineer's anticipated building movements by the architect or the contractor

建筑性能的目标

目前美国和国际建筑规范遵循ASCE7-10中规定的地震力和风力标准（图2和3）（ASCE，2011）。对于普通的建筑物，以风险为目标的最大可能地震力（MCER）是以50年内发生坍塌机率为1%的目标来确定的。在美国，大多数情况下，这相当于一个大约2000年发生一次的事件。“设计地震力”被定义为这些最大可能地震力的2/3，平均起来相当于50年内超越概率为10%（475年一遇）。包含在这些概率计算中的数据分布显示设计地震复发间隔为200年到800年不等。

对于风力，其标准是按一个结构系统中的单一结构构件达到其极限状态时回归周期为700年来规定的，这相当于50年内超越概率目标为10%。

在上述的情况下，这些主要的结构体框架设计的标准在进行概率风险讨论时都包括了50年的参照点，这被制订并记录在当今的建筑规范中。

从地震的角度来看，许多人会认为，按照当前国际建筑设计标准进行全面地设计，并且避免不规则体系的建筑结构在地震中会表现良好。符合设计标准的新建建筑物由近期地震所造成的结构破坏在大部分情况下是可修的，只有少数情况例外。今天最严重的地震破坏通常发生在老旧建筑物的薄弱处或者发生在没有按照设计标准或类似等价标准设计的建筑物中。

为使建筑物达到100年的使用期限来变更我们当前的建筑结构抗震设计标准可能不会发生。然而，讨论为建筑物外墙体系或其他附属结构体系的设计变更设计术语，并开始设定100年这样一个观念是具有重要意义的。一个100年内发生概率为2%的事件相当于大约2000年一遇与50年内发生概率为1%的事件是相同的。

抗震设计的一个发展方向是在未来的建筑规范中采用更多的性能化设计（PBD）方法，并在分析中包络多个不同水平的地面震动（旧金山建筑部门，2008；PEER，2010）。尽管规范对此没有强制规定，但是除了50年发生概率为1%的最大可能地震事件之外，我们现在也应考虑低级水平的可维护性事件。今天，可维护性是指在30年内超越概率为50%（43年一遇）的地震作用下，结构体系仍处于弹性状态。分析的第二个层次也是与现今的热门话题，即在结构框架使用寿命中与破坏极限和可修性相关的非建筑结构体系。

因为构筑物会随着时间的推移改变和适应，保证在30年内可维护事件的发生概率为50%，并且用100年内发生概率为2%重新定义最大可能地震事件，将形成一个恰当的参考体系。这样不仅为建筑结构的耐久性及其影响建筑使用寿命的最重要的组成部分，如外围结构体系，考虑到短期灾害的影响，也设定了一个到所希望的思考模式。

延长建筑使用寿命

地震中的使用寿命

地震所带来的损失中有大约70%是来自非结构构件的外围幕墙和构筑物的破坏，而非建筑物的倒塌。这些非结构构件在哪些位置出现问题最多呢？其一，是幕墙的连接节点，尤其是在拐角处的连接节点，因为它们通常在设计和施工过程中没有生效。对幕墙进行过工程处理的项目，如高层商业塔楼，通常都有精心设计的外观。但不幸的是，给予大多数的住宅建筑外围体系的是最少的结构设计，顶多只是提供一系列标准的细节图。通常，建筑师和承包商对场地上预期的建筑物移动缺乏认识，因而他们不会给建筑物设置合理的变形缝。如果考虑了结构变形，那么就会预见到外立面体会在楼层和拐角处发生弯曲或开裂。建筑任何主要的侧向位移都会给建筑物带来破坏并需要修复。不幸的是，当修复发

on site, and appropriate jointing for such movement is passed over. If movement is considered, the expectation is that the system will flex or crack at floor and corner joint lines. Any major lateral movements of the building will bring damage and require repair. Unfortunately that repair may exceed the value of the building when it occurs after completion of the project.

One current example seen in a number of cities outside the U.S., some with seismic concerns, are 60-plus-story buildings constructed with exterior cladding comprised of infill hollow clay tile or brick and plaster with no movement joint allowances. This type of enclosure is cheap to build, but it will crack. Water infiltration will affect its long-term durability, and there is a high probability of bricks "raining" onto the street below during an earthquake. As shown in Figure 4, the "primary" structural frames of these buildings are fairly well designed. However, significant damage will occur in even a moderate earthquake due to infill brick falling off the building's exterior. This exterior infill brick system is banned in U.S. high seismic regions and many other countries for the obvious life-safety reasons. However, because it is one of the cheapest building exteriors, it is frequently still used, especially in developing countries with less-stringent building codes.

For improved survivability, building enclosures need to be explicitly designed, detailed, and jointed for the true movements that the base building frame will experience without damage during service-level earthquakes. At the design and MCER earthquake level, they also need to include a strategy for protecting the public at ground level from falling objects or, better yet, be designed such that the glass, brick, or other items will not fall from the building. Curtain-wall systems today generally can achieve these goals. Infill systems can work well, but if not specifically and appropriately designed, they lead to improper systems. Infill brick systems such as those shown in Figure 4 represent a significant long-term liability in any location subject to seismic activity.

This may seem obvious, but it is one of the biggest and most common mistakes in the design of residential buildings in emerging markets. It is an attention to detail that is too frequently overlooked.

Two other areas of significant damage to building contents following an earthquake are water damage due to inappropriately anchored water tanks or piping systems and damage caused by falling bookcases and other shelving systems. To better understand the performance of these nonstructural components in an earthquake and determine best-practice yet economical solutions for protecting secondary systems, the University of San Diego recently tested a

Figure 4. Brick Infill Cladding with No Movement Joints (source: Magnusson Klemencic Associates)
图4. 无变形缝的填充砖幕墙 （出处：马格努松·克莱门契奇有限公司）

生在在项目完工之后时，这个修复的成本往往会超出建筑物本身的价值。

以美国之外的一些城市为例，可以发现存在抗震设计隐患的多为60层以上的建筑物，它们的外围幕墙包括填充空心黏土瓦片或水泥砖块，并且不设置变形缝。这种类型的幕墙造价低廉，但是容易开裂。水的渗入会影响它的长期耐久性，并且，在地震发生的时候，一场“砖雨”洒落在街头的几率将会非常的高。如图4所示，这些建筑的“主要”结构体系设计地相当好。然而，即使是中度地震下，建筑外围填充砖的掉落也会对建筑物造成巨大的破坏。这种内填充砖系统由于其生命安全原因在美国高强地震带及许多其他国家被禁止使用。然而，由于它是最便宜的外围幕墙结构之一，它仍在被广泛使用，尤其在一些缺乏严格建筑规范的发展中国家中。

为了延长耐久性，建筑的外围结构需要按照真实的变形进行明确地设计、绘制详图和连接，从而使基本的建筑主体在经历正常服务水平地震时，有合理的位移，不产生严重的破坏。对于设计地震水平和最大可能地震水平下，它们还需要采取措施以保护地面公众不为掉落物体所伤。或者更好的，在地震过程中，使设计的幕墙，诸如玻璃、砖块或其它构件不从建筑物中掉落。通常情况下，当今的幕墙系统可以达到这些目标。内填充砖体系可以正常地工作，但如果这个系统不经过特殊和合理的设计，它们将是不合理的体系。内填充砖体系如图4中所示，在任何有地震活动的地方承担着重要的长期服务职责。

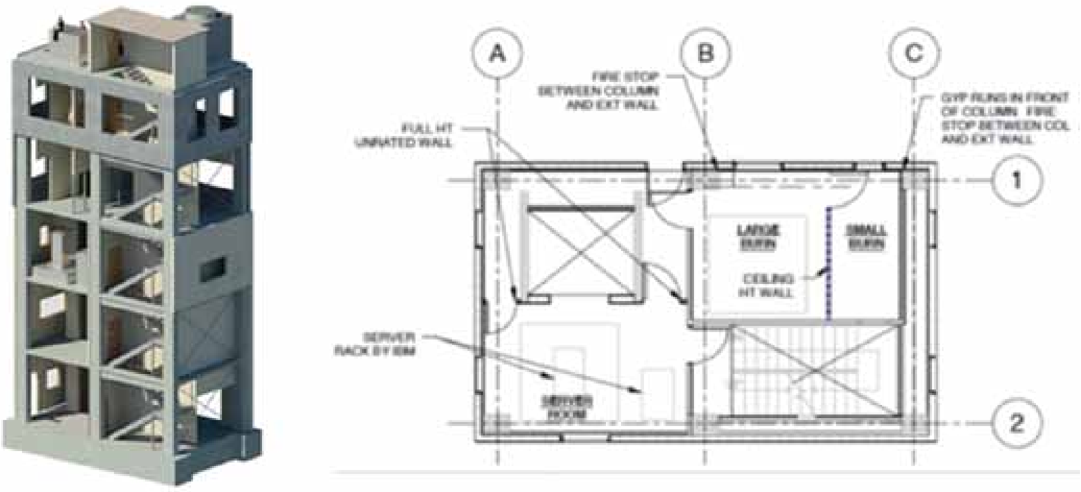

Figure 5. UCSD Seismic Test Specimen – Nonstructural Elements and Components (source: USCD)
图5. 圣地亚哥大学抗震试验样本 – 非结构构件和单元（出处：圣地亚哥大学）

Figure 6. Joplin, Missouri – May 2011 (source: Charlie Riedel, Associate Press)
图6. 密苏里州乔普林 – 2011年5月 （出处：查理•里德尔，美联社）

full-scale five-story concrete building on their shake table (see Figure 5) (Hutchinson, 2009). These tests, funded by the National Science Foundation, the Charles Pankow Foundation, and other industry leaders and material suppliers, involved over 4 years of preparation and planning. A full range of systems are being evaluated, including a functioning passenger elevator, piping, sprinklers, HVAC, interior walls, suspended ceilings, cladding systems, and building contents, as well as both passive and active fire systems. The data from this testing are still being evaluated but will eventually be available to the general public.

Longevity in Wind

Wind design is another area of inconsistency between high- and low-rise residential construction. This area likely needs ongoing attention, especially given the increasing frequency of hurricanes, typhoons, and tornados. Communities in the U.S. Midwest, with their propensity for lightweight stick-framed construction, are very vulnerable to tornados.

The building codes currently do not address designing for tornados, so the losses seen in areas where they occur are not unexpected. Figure 6, showing Joplin, Missouri, following a tornado in May 2011, is very telling regarding the survivability of lightweight wood construction compared to heavier-weight buildings, even though neither was specifically designed to resist a tornado.

Weight is your friend when resisting wind. Figure 7 shows that brick helped hold the building walls together, but the lightweight wood roofs were all blown off. Once the roof was lost, and without a stiff backing of the floor and roof diaphragms, not much remained of these buildings after the tornado. Lightweight building designs like these, even with brick veneer cladding, certainly were not a safe place to ride out the storm.

While the statistically derived code-level wind storm may not equate to the force of a tornado, our fundamental building system choices in these U.S. areas seem to be in need of evaluation. Perhaps this is a location for architects to work on a new building typology. More compact development with heavier building frames or cladding systems, combined with green landscaped roofs, can answer several sustainability goals and offer better protection in extreme wind events. The concrete industry is just beginning to focus on this in earnest.

Improving Longevity – Aesthetics and Avoiding Functional Obsolescence

One of the challenges for buildings with longer durations is that they need to remain functionally viable and desirable. Open floor plans and flexible spaces that allow interior walls to change over time can be

Figure 7. Brick Cladding with Wood-Framed Walls and Roofs (source: Charlie Riedel, Associate Press)
图7. 有木结构墙和屋顶的砖围墙（出处：查理•里德尔，美联社）

这似乎是显而易见的，但它是在新兴市场的住宅建筑设计中的最大和最常见的错误之一。对细节的关注往往最常被忽视。

地震后，构筑物被破坏严重的其它两个地方是由于没有合理锚固的水箱或管道系统导致的水的破坏，以及书柜和货架坠落产生的破坏。为了更好的理解这些非结构构件在地震中的性能，并为二级体系决定最佳且经济的可实施保护方案， 圣地亚哥大学近日在他们的震台上对一个实际比例的5层混凝土结构进行了测试（图5）（哈钦森，2009）。这些实验由国家科学基金会，查尔斯•潘科夫（Charles Pankow）基金会和其他行业领导者和材料供应商赞助，经历了4年多的准备和计划。对各个体系进行全方位地评估，包括正常运作的乘客电梯、管道、喷头、采暖通风和空调、内墙、吊顶、幕墙系统，建筑构筑物，以及被动和主动消防系统。从这个实验得到的的数据仍在评估中，但最终将会提供给大众。

在风力作用下的使用寿命

抗风设计是另外一个在高层和低层住宅建筑中不一样的地方。这个方面可能需要持续关注，特别是考虑到飓风，台风，龙卷风发生频率越来越高。美国中西部的社区经常使用的轻质杆结构建筑，及易遭到龙卷风的破坏。

现今建筑结构规范中没有明确的抵抗龙卷风的设计准则，因此在发生龙卷风的区域遭受损失并不意外。在密苏里州乔普林于2011年5月经历了一场龙卷风后，图6对该区的轻质木结构建筑和质量较重的建筑物的耐久性能进行比较，尽管它们都没有为抵御龙卷风进行过特别地设计。

抗风时，重量也是有益的。图7表明，砖块可以帮助建筑的墙体聚拢在一起，但是轻质木结构的房屋都被风刮走了。一旦屋顶被刮走，楼板和屋顶板后面就没有了刚性支撑，龙卷风之后这些房屋已所剩无几。像这样的轻质房屋设计，即使用了砖幕墙的设计，也不会是一个安全的地方来安然渡过风暴。

然而，根据规范计算的风力不能和龙卷风的风力同日而语，看来我们需要对美国这些区域的基本建筑类型进行评估。也许，建筑师可以从这里开始工作，创造出一个新的建筑类型。如由更重的建筑结构或幕墙系统，以及配有绿色景观的屋顶而组成的更加紧密的住宅小区，可以达到一些可持续发展的目标，并对房屋在遭遇到强风时提供更好的保护。混凝土业界正开始认真的关注这个问题。

Figure 8. Aqua Tower, Chicago (source: Magnusson Klemencic Associates)
图8. 水族塔，芝加哥（出处：马格努松·克莱门契奇有限公司）

tremendously beneficial. Mechanical and plumbing systems that allow for future adjustments of wet areas such as bathrooms and kitchens are also a big plus. In residential concrete construction, eliminating interior beams is the first way to achieve this flexibility.

Lastly, and possibly one of the most significant, issues, is that building aesthetics count. If a building ever has a chance to stay around for 100 or more years, it needs an identity and quality level that the next generation will want to keep. While not the focus of this paper, quality architecture and design are worth the investment.

One example of these ideas coming together is Aqua tower in Chicago (see Figure 8) (Aqua Tower, 2010). A mixed hotel and residential development, Aqua's notable building image was neither overly expensive nor complicated to achieve. The building's flat plate construction with no beams allows for open and flexible floor programming, and the elimination of post-tensioning in the bathroom and kitchen areas means that the unit layouts, within limits, can change with time. Enhanced durability measures also went into the concrete mix designs, and, among other protection measures, all the exposed concrete includes epoxy-coated rebar.

Looking Forward

The current migration trend into cities creates both opportunities and challenges. Are we appropriately evaluating where we build, how we build, and how long we expect the buildings to last? Are we adequately considering future replacement costs when making infrastructure decisions today?

Ensuring the longevity of the core residential building supply, making smart choices based on double-bottom-line evaluations, and building not just for today but for the needs of future generations are all important for the future.

This paper presents the following recommendations:

- More regular consideration of a 100-year design life for the primary systems that go into the residential multi-story building inventory. This needs to include base building frames and exterior enclosure systems which, when designed and detailed correctly, can provide 100 or more years of usable life.

延长使用寿命 - 美学和避免丧失功能

长时间以来，延长建筑使用寿命的挑战之一是它们需要保持功能的可行和可取。开放的平面布置以及允许内墙随时间变换的灵活空间是极其有益的。允许在潮湿区域如盥洗室和厨房内布置的机械和管道系统根据未来需求进行调整，也非常有用。在混凝土住宅建筑中，消除内梁是达到空间灵活性的第一个方法。

最后，也可能是最重要的议题之一，是建筑的美学价值。如果建筑物有机会保留大约100年以上，它就必须达到一定特色和质量水平使得下一代想要留下它。虽然这不是本文的重点，但是高质量的建筑和设计是值得投资的。

汇集这些想法的案例之一就是位于芝加哥的Aqua大厦（图8）（Aqua大厦，2010）。它是一个酒店和住宅混合的开发项目，其著名建筑的形象既不昂贵，也不复杂。此塔的无梁楼板允许开放和灵活的楼面布置。消除浴室和厨房区预应力混凝土结构意味着单元里的布局，在一定限度内，可以随时间而改变。并且，对混凝土配合比设计采取了加强耐久性的措施，其它保护措施中有对外露的混凝土都使用了有环氧树脂涂层钢筋。

展望

目前向城市迁移的趋势同时创造了机遇与挑战。我们是否适当地评估了建造地点、建造方式、以及我们希望建筑物能够维持多久？在我们今天决定基础设施的建设时，是否足够考虑到了将来的替换成本？

确保核心住宅建筑供给的长期使用寿命，根据双底线评估方法做出明智的选择，建造出不仅满足当今的需求也同时满足后代的需求的建筑物，对未来都是很重要的。

本文提出如下建议：

- 将100年设为建筑主体结构的设计年限更多地应用到多层住宅结构设计中。这需要同时应用于基本建筑结构和外围结构体系，当对建筑物进行正确的结构设计和细节设计后，建筑物的使用寿命可达100年以上。
- 当采用用隐含碳作为一个度量标准来进行建筑选型时，需要着重于比较数据，而不是绝对值。在评估中包括主体建筑的长期使用价值、重复利用价值或再售价值。
- 重置参照体系，考虑将ASCE 7-10的考虑的最大可能地震从50年发生概率为1%改为100年内发生概率为2%。

- When using embodied carbon as a metric for evaluating building choices, focus on comparative data and not on absolute numbers. Include the long-term re-use or resale value of the base building within that evaluation.
- To reset the frame of reference, consider changing ASCE 7-10's Maximum Considered Earthquake (MCER) from 1% probability in 50 years to 2% probability in 100 years.
- For building serviceability, include an analysis of a service-level earthquake with a 50% probability in 30 years, with an essentially elastic structural performance and minimal damage to nonstructural primary building elements and components.
- In high wind zones subject to hurricanes and tornados, improve the survivability of building systems with more robust construction choices.
- Design 100-year buildings to be desirable, durable, and adaptable. Architectural interest and quality finishes count. Even if the building program stays the same, wall locations, mechanical systems, and finishes should be adaptable to future modifications.

- 建筑的可维护性，应分析在30年内发生概率为50%的正常使用地震水平下的结构构件基本处于弹性，非结构构件发生最小的破坏。
- 在遭受台风和龙卷风的高强度风区，通过使用更为强壮的建筑类型来提高建筑系统的耐久性。
- 将100年的建筑物设计成为可取的、耐用的和适应性强的建筑，建筑功能和建筑完成面质量具有重要的价值。即使建筑方案不变，墙的位置、机电系统和建筑完成面应该适应未来的调整。

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