Considerations in the Recycling of Urban Parking Garages

by

Michael Johannes Paul

B.A., Dartmouth College, 1973

Submitted in Partial Fulfillment
of the Requirements for the
Degrees of
Master of Architecture
and
Master of Science in Civil Engineering
at the
Massachusetts Institute of Technology
February, 1981

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Michael Johannes Paul

Submitted to the Department of Civil Engineering and to the Department of Architecture on February 6, 1981, in partial fulfillment of the requirements for the degrees of Master of Science in Civil Engineering and Master of Architecture

Abstract

Because of the decreasing use of private automobiles in city centers and because of usual development pressures, some urban parking garages will become available for replacement or recycling. The choice between replacement or recycling of an abandoned garage is based on cost, but many other factors influence this decision. The suitability of a garage for recycling can often be determined by the consideration of three simple indicators: the type of garage, the horizontal depth of the building, and the typical floor-to-ceiling height. Following the determination of basic suitability, several architectural and structural issues must be considered in order to identify potential problems in the intended recycling and in order to discover practical solutions to these problems.

The determination of suitability and the consideration of architectural and structural problems are discussed generally, and are demonstrated in the study of the West Garage.

Thesis Supervisor: James M. Becker
Title: Associate Professor of Civil Engineering
ACKNOWLEDGEMENTS

Institute regulations permit only one signature as that of supervisor in the title sheet of this thesis. I was fortunate to benefit from two advisors. The counsel and encouragement of both Edward Allen, Associate Professor of Architecture, and James Becker, Associate Professor of Civil Engineering, illuminated the work on this thesis.

Bob Keuhn, Randy Lewis, and Fred Palegrini were most helpful as sources of information or with suggestions on how to obtain it.

I extend my appreciation to the teachers who have variously inspired, directed, and cajoled me: Demetria and Larkin; Sullivan; Baird, Beckmann, Jernstedt, and Morris; Becker, Halasz, Smith, and Tremaglio.

Finally, I thank family and friends for extraordinary patience and quite support: GJP, KPC, LGP, and SRP; JCR, NPR, and RCT; PFS.

Thank you all.
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part I: INTRODUCTION

Part I introduces the organization of the manuscript, explains the choice of topic, defines terms and scope of the discussion, and notes some sources. Part II describes the motives for recycling a parking garage, especially in regard to cost. Part III discusses architectural and structural considerations that must be made in a brief feasibility study of the recycling of a parking garage. Part IV examines the suitability of recycling the West Garage in the light of the general considerations of the previous part. Part V offers some conclusions regarding the recycling of urban parking garages and regarding the considerations of parts III and IV.

This thesis assumes that automobile parking garages located in urban areas will become available for recycling. This assumption does not suggest that garages will be abandoned in a wholesale fashion within the next few years. Nor does it suggest that all abandoned garages will be suitable for recycling. Rather, the assumption suggests that over
next ten years some urban parking garages will become available for recycling just as many other urban buildings have become available over the past ten years. Indeed examples of recycled parking garages can be cited. (1)*

Several observations support this assumption. First, the use and storage of private automobiles in urban centers is likely to decrease. A longstanding goal of national transportation policy has been to reduce urban congestion by encouraging the use of public transportation while discouraging the use of private autos. (2) Though both programs and results under this policy have been mixed, such efforts will continue. Both federal and local environmental protection authorities have proscribed the use of autos in urban areas in attempt to improve air quality. Comprehensive urban planning efforts have recommended the restriction of auto use in urban areas, both to relieve air pollution and urban congestion, and to improve the general quality of urban life. The creation of auto-free pedestrian zones in downtown areas has grown under pressure from merchants, local government authorities, and the public. The cost of owning and operating private autos is likely to increase so that their use in intra-urban transportation will cease to be economically competitive with other public modes of transportation.

Second, urban parking garages are likely to become available for recycling due to increasing development pressures. Older cities eagerly predict the return of people, *All footnotes are at the end of the text.*
business, and money to their centers. The substantiation of this rejuvenation is mixed, though the self-fulfilling nature of such an attitude is effective. Regardless, the more usual development processes will encourage replacement or recycling of parking garages in order to make better use of valuable urban land. Cities are being rezoned to allow residential use and to encourage the development of full rich "mixed use" in urban centers. This activity will augment the usual strong demand for urban housing.

(It is possible that an increase in residential use will also increase the demand for storage facilities for autos owned by urban dwellers. Witness the introduction of "parking condominiums". This demand would indicate that existing garages will not be abandoned and that new garages will be required. The actual scenario depends on many factors. A decisive factor will be the availability of attractive alternative transportation.)

Third, interest in recycling older buildings will grow and encompass more buildings of many types. More older buildings are being recognized as architecture worthy of preservation. As the cost of new construction soars, the alternative of recycling existing buildings will become more economically attractive. The creative reuse of the energy investment in an existing building will be regarded as a more responsible decision, if not more cost effective, than the loss of this investment through demolition.
On the basis of these considerations, if it is not conclusive that urban parking garages will become available for recycling, at least it is certain that the possibility of such availability is strong.

The terms used to describe the operations performed on older buildings have proliferated as the interest and activity in this area have grown. Following are definitions of and distinctions between some of these terms:

To **adapt** an existing building is to physically modify as is necessary to accommodate a change in use.

To **convert** is to give a new use through major physical changes.

To **recycle** is to change either the use or the physical characteristics, or both.

To **rehabilitate** is to improve physical conditions while retaining the existing use. This term usually applies to housing.

To **restore** is to return an existing structure to an earlier, if not original, form. Use need not change but to the extent that it interferes with physical restoration.

To **reuse** is to change the use of an existing building. Physical alteration is minor or major, as required by the new use.
The term "recycle" subsumes the others; it is most general. Recycling parking garages, as discussed in this thesis, implies a definite change in use and considerable physical alteration.

Though the original intent was to study the change from auto parking to mixed use, this thesis concentrates on the change in use from parking to housing. This shift arose partly because of the restrictive requirements of business and mercantile use. These uses require floor-to-ceiling heights greater than those typically offered in parking garages. Also, design live loads exceed those for which garages are typically designed. These problems are further discussed in part III. In addition, early analyses of garages for recycling indicated the programmatic appropriateness of residential reuse. The thesis examines the recycling of garages for residential use with the certainty that such analysis will prove instructive when considering other uses.

The type of parking garage examined in this thesis can be described as follows:

- **Above ground** location allows conversion to new use where natural light is required;
- **Free standing** condition precludes determination of use or restrictive engineering problems due to attachment to or inclusion within another structure;
Multi-story height insures that there is enough of the original building to warrant recycling and to influence new construction.

Most of the parking garages which were encountered in early stages of thesis work were constructed of concrete. Informal observation suggests that a majority of multi-story garages are constructed of concrete. Consequently, the thesis considers only concrete parking garages. The West Garage studied in part IV is constructed of precast-prestressed and cast-in-place reinforced concrete. The considerations of part III discuss cast-in-place, precast, prestressed, and posttensioned concrete construction.

It is useful to note certain dissimilarities between the recycling of parking garages and the preservation or recycling of historic or industrial buildings which is in vogue. Industrial buildings were usually constructed to withstand far greater loading than that which they experience in reuse. Design live loads typically exceed 100 p.s.f. even for old industrial buildings. Current design live loads for probable new uses do not exceed 100 p.s.f. Assuming the structure is intact, all but the most unusual loads can be accommodated by the usual typical industrial building. As discussed in part III, garages were seldom designed for live loads as great as 100 p.s.f. The more typical design live load for garages is between 50 to 75 p.s.f. Garages are not over structured and thus able to accommodate any reuse,
as are industrial buildings.

Mill buildings of the nineteenth century which currently are much recycled are constructed of heavy timber and masonry bearing wall in a fashion that allows easy modification. Most parking garages, and all of those considered in this thesis, are constructed of reinforced concrete, which is much more difficult to alter. The wood framing of the mill buildings is considered appealing and is frequently simply cleaned and left exposed. Concrete does not enjoy such aesthetic appreciation. Finishing costs will be high in the recycling of a concrete garage.

Industrial buildings usually were built with commodious floor-to-ceiling heights to accommodate equipment. Floor-to-ceiling heights in garages were designed to accommodate only cars, in the case of many hoist facilities, or upright walking operators in the case of ramp garages. The short floor-to-ceiling heights in garages can pose serious difficulties for reuse.

The recycling of most buildings requires the preservation or restoration of valued exteriors; interiors are frequently gutted and entirely reconstructed. The exteriors of garages are not usually valued. Either they do not exist at all, they are unattractive, or they are inappropriate or unusable in the need to enclose the building for reuse. The interior of the garage is effectively gutted.
Several codes were used in the preparation of this manuscript. **HUD Minimum Property Standards** for multi-family housing was consulted in developing the architectural schemes for the recycled West Garage. The **BOCA Basic Building Code/1978** was a source of architectural and structural requirements and building limitations. **Building Code Requirements for Reinforced Concrete (ACI 318-77)** served as a source of structural requirements and methods of engineering analysis.
This part examines the advantages and the disadvantages in recycling an urban parking garage. Cost is the fundamental criterion in the decision whether to recycle. This decision is influenced by many factors, however.

Two options exist for the disposition of an urban parking garage that is no longer used for the storage of private automobiles. The garage can be demolished and replaced or the garage can be recycled for reuse.

Many factors influence the choice between these two options. Government policy and program may favor one action over the other through mandate or incentive. Zoning may prohibit certain uses. Local building codes may adjudge the building inadequate or inappropriate for use other than parking. Redevelopment authorities may grant variances or bonuses for the reuse of existing buildings. Historical commissions may prohibit demolition. Financing assistance and tax incentives by state and federal authorities may be contingent on a particular action. Organizations of concerned citizens
may exert political influence to make easier or more difficult a course of action.

Because of the nature of the economy and of the government of this country, cost is of the fundamental criterion in deciding between replacement and recycling of an available building. This gross criterion excepts some of the many other factors but includes most. The following discussion of cost is presented from the perspective of the developer, who is instrumental in making the decision. From this perspective there are three options. The existing building can be recycled. The building can be replaced. The building can be ignored and new construction can occur on other undeveloped property. This last option is discounted. It is assumed that there are few such undeveloped parcels in urban centers.

An actual decision is dependent on the particulars. A truly meaningful comparison between the cost of recycling and the cost of replacement must be for a specific property and a specific program. Development conditions due to the market, the suitability of the existing building to the intended reuse, and the physical condition of the building can be decisive. However, it is possible to compare the cost of recycling and the cost of replacement in a relative manner and to draw some general conclusions.

Data furnished by a housing developer for the year 1978 show that total cost for new construction and that for
recycling are very similar when compared by unit measure.\(^{(3)}\) Based on gross square footage, the cost of recycling is less than that for new construction:

- **Recycling:** $27.25/s.f.,
- **New Construction:** $29.13/s.f.

Based on living unit, the cost of recycling is greater:

- **Recycling:** $33,182/l.u.,
- **New Construction:** $28,577/l.u.

The inefficient use of total space in recycled buildings accounts for this discrepancy in comparisons. This matter is discussed further in part III. If comparisons were based on gross cubic footage it is likely that recycling would show a greater relative cost.

Although these simple comparisons use total cost, it should be noted that the cost of new construction does not usually include the cost of demolition of existing buildings. A true comparison between the cost of recycling and that of replacement, instead of merely new construction, would probably favor recycling by any measure.

Compared in this simple and admittedly abstract manner, the cost of recycling an existing building is at least no greater than the cost of replacing it with new construction.

Many factors influence the decision based on cost. In recycling, construction begins with the gross structure. This structure was built at "old" costs and replacement by an equivalent would be expensive. However, the original
structure was not built for the intended new use and may prove difficult to adapt. The structure was not designed to allow easy installation and distribution of mechanical services. Installing such services in an existing concrete building requires costly coring and cutting. Because of the existence of the structure, the construction period is shorter for recycling than for new construction. The time that the higher-interest construction loan must be carried is shorter. However, during this period the higher cost of land with an existing building must be carried. Because of the existing structure, renovation may proceed in a piecemeal fashion. Common spaces and models may be quickly finished to hasten rental commitments. However, this possibility may be negated by the manner in which building trades prefer to work, from top to bottom through the whole building.

Construction costs are more predictable and controllable because common surprises that accompany the construction of the substructure have already been encountered. Other hidden problems offset this advantage. Complete construction documents may be difficult to obtain, especially for older garages. Without such documents the placement of reinforcement and design loads are not known. Testing to discover such information and to establish the strength of members is expensive. Too, even if construction documents are available, discrepancies between "as drawn" and "as built" will happen,
especially in older garages. Discovery of these discrepancies during construction can require costly changes in design and procedure.

Recycling a building is labor intensive. As the relative cost of materials gains on that of labor in the total cost of construction, this intensiveness will become important. Recycling requires little use of highly paid special trades such as equipment operators or steel workers. However, because of the ever changing conditions and the many special problems encountered in any renovation, straightforward production work is hampered and the trades that are needed must be skilled. Because recycling is labor intensive, it is energy conserving. Energy for the fabrication of a new structure is not necessary. Neither is energy invested in the original construction wasted through demolition. These labor and energy considerations will gain importance in the future.

If the garage is a registered historic building or if it is located in a historic district, the same accelerated depreciation used for new construction can be applied to recycling. These costs can be amortized over five years rather than over the remaining life of the building. The cost of demolition must be capitalized and added to the value of the land on which replacement new construction is located. Further, accelerated depreciation is not allowed for new construction located on the site of a demolished
historic building.

The recycling of an existing garage may gain assistance, benefits, or development bonuses from federal, state, or local authorities. However, these incentives are likely to be encumbered by restrictions of offsetting value.

Beyond the above influences on the cost decision, several other advantages in recycling a parking garage merit attention. It is often easier to "sell" a proposal to recycle a building than to sell its demolition and replacement to concerned and politically influential groups. If the existing building is valued, recycling can preserve and enhance. If aspects of the building are disliked, recycling can improve. In either case the completed building is easier to visualize because it already exists in fundamental form. This compares favorably to the difficulty inherent in asking concerned people to understand a building that does not exist at all. In addition, the opposition to demolition is avoided. Too, if preservation and reuse of older buildings are important to local authorities, the developer can gain allies and a foot-in-the-door by proposing to recycle a building rather than to replace it. This assistance may prove valuable in seeking permits and variances from these same authorities.

The very inefficient use of space that increases the relative cost of conversion is also a benefit. Compared to new housing, apartments in a recycled building tend to be
larger and unusual. The depth of garages that is greater than that necessary for "ideal" housing allows larger rooms and more storage. In older garages the floor-to-ceiling height that is greater than the usual minimum creates spaciousness. Balconies set in from the edge to decrease the depth of the apartments also are an intrinsic benefit. The spacing of columns, not intended for residential use, can create distinctive spaces. Altogether the quality of apartments in a recycled building may be superior to that of modern luxury apartments designed to meet current minimum standards. Though this quality may not be recouped in higher rent, it remains as a real benefit of recycling.
Not all parking garages that are available for recycling can be recycled. This part discusses essential issues which must be considered in a brief study conducted to determine the architectural and structural feasibility of recycling an urban parking garage into housing.

Simple Indicators

Three gross physical characteristics can quickly indicate whether a particular garage is suitable for recycling.

Parking garages can be classified by the manner in which autos are moved within the garage. Several types are shown in Figure 3.1. The primary distinction is between hoist and ramp garages. Ramps may connect full-level floors, or they may connect split-level floors. The ramps may have several configurations and may occur internally or externally. Finally, the floors themselves may be continuously ramped.

The type of garage can quickly determine suitability for recycling. Hoist garages present difficulties because
Figure 3.1 Types of garages according to manner of moving autos within building. ( Adapted from Metropolitan Parking Structures by Dietrich Klose.)
floor-to-ceiling heights of the storage levels frequently are only great enough to accommodate autos. One of the hoist garages included in the descriptive analysis of Table 3.1 has an average floor-to-ceiling height of 6'-0". The mean for all four hoist garages is only 6'-9". Such heights violate minimum code standards for inhabitable spaces. Ramped garages with level floors, too often present difficulties because of floor-to-ceiling heights. However, the problems are not as acute and require further consideration as given below.

Ramped-floor garages in almost all cases are not suitable for recycling. The typical slope of 3% gives a rise of almost 6" over 16'. The great length of the building and the short floor-to-ceiling height combine with this slope to produce space of uninhabitable height if the length of the floor is leveled. Intermittent leveling complicates the provision of continuous access and is difficult and expensive to accomplish. The increase in dead load due to such leveling would be excessive.

The depth of the garage can quickly determine suitability for recycling. As listed in Table 3.1, the median shortest dimension for all garages is 124 feet. The median gross square footage is 25,212. Garages are large, deep buildings. Klose notes that ramp garages typically require "a plot of certain minimum size which roughly amounts to 100 x 100 feet (10,000 s.f.)." The double loaded residential building, preferred by developers for its efficient use of space,
### Type of Garage

<table>
<thead>
<tr>
<th>Type of Garage</th>
<th>All types N=17</th>
<th>Hoist N=4</th>
<th>Full-level N=4</th>
<th>Split-level N=6</th>
<th>Helical Ramp N=3</th>
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<tr>
<td><strong>Length of Short Side (ft)</strong></td>
<td>Median 114.5</td>
<td>91</td>
<td>118.5</td>
<td>126</td>
<td>106</td>
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<td>Mean 124</td>
<td>90.5</td>
<td>127</td>
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<td>Range 65-240</td>
<td>65-115</td>
<td>95.5-174</td>
<td>94-240</td>
<td>103-165</td>
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<tr>
<td><strong>Area (sq ft)</strong></td>
<td>Median 25,212</td>
<td>12,274</td>
<td>36,095</td>
<td>25,689</td>
<td>32,648</td>
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<tr>
<td></td>
<td>Mean 33,138</td>
<td>11,543</td>
<td>39,358</td>
<td>43,565</td>
<td>32,780</td>
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<td>Range 3,876</td>
<td>3,876</td>
<td>25,212</td>
<td>19,364</td>
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<td></td>
<td></td>
<td>-108,864</td>
<td>-108,864</td>
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<tr>
<td><strong>Height in Stories</strong></td>
<td>Median 5</td>
<td>7.5</td>
<td>3.3</td>
<td>3.5</td>
<td>5.3</td>
</tr>
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<td>Mean 5.1</td>
<td>8</td>
<td>3.3</td>
<td>4</td>
<td>5</td>
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<tr>
<td></td>
<td>Range 2-12</td>
<td>6-12</td>
<td>2-4.5</td>
<td>2-7</td>
<td>5-6</td>
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<tr>
<td><strong>Height in Feet</strong></td>
<td>Median 48</td>
<td>68</td>
<td>31.2</td>
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<td>Mean 46.8</td>
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<td>32</td>
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<td>21.5-44</td>
<td>16-67</td>
<td>57-63</td>
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<td><strong>Floor to Ceiling Ht. (ft)</strong></td>
<td>Median 7.1</td>
<td>6.4</td>
<td>7.7</td>
<td>7.1</td>
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<tr>
<td></td>
<td>Mean 7.1</td>
<td>6.8</td>
<td>7.9</td>
<td>7.1</td>
<td>7.3</td>
</tr>
<tr>
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<td>Range 6.0-9.1</td>
<td>6.0-8.3</td>
<td>7.1-9.1</td>
<td>6.8-7.9</td>
<td>6.9-7.8</td>
</tr>
</tbody>
</table>

Table 3.1 Descriptive data for selected garages from Metropolitan Parking Garages by Dietrich Klose. Garages were chosen according to the ability to obtain information included in this table. No attempt was made to sample randomly.
typically measures 60 - 70 feet in depth. If apartment widths are held constant, square footage will increase as the building achieves greater depth. This represents an inefficient use of space to the developer, though there are benefits to the dweller. This issue is discussed throughout the thesis. These greater depths leave interior areas of the apartments with little natural light unless they are able to borrow light from an interior light well. If it is not possible to bring light into the center of a deep building, then the center can be used for storage, circulation, and other functions which do not require natural light. Expanding this unlit center zone effectively pushes the interior ends of the apartments toward the outside wall and closer to natural light.

A problem in this type of scheme is that the unlit backs of the apartments are often occupied by kitchens and bathrooms. Natural light in the bathroom is a low priority and is often neglected in the push and pull of compromise, though the lack of it is unfortunate. The minimal unlit kitchens that follow from this design scheme are a terrible consequence of the search for efficiency. Certainly the quality of "the kitchen at home", where studying, talking, laughing, reading the paper, and potting the plants were activities more frequent and more essential than mere cooking and eating, makes these designs born of efficiency questionable. (6)
Returning to the problem of depth, there are two solutions where the depth of garages is too great. First, enclosed central light wells will bring light into the building, that can then be borrowed by the back rooms of the apartments through interior windows. This light well will also serve to push the apartment toward the outside edge.

Second, selective demolition of the building from the outside will decrease the depth. If such demolition creates an indented edge, the perimeter of the building will also be increased, giving more exterior wall.

Creation of an enclosed light well is often easier than demolition of a portion of the exterior edges. Garages with level floors connected by internal ramps often provide such a space when the ramps are removed. The hoistway in a hoist garage is such a space provided gratis. Removing portions of exterior edges usually involves removal of edge beams which must be replaced if the new edge does not occur at an interior beam. The depth can be decreased by providing a balcony at the outside edge. Though this option does give solar shading and allows enclosure to be simply constructed between floors, it does not gain light for the interior areas of the apartment.

The floor-to-ceiling height can quickly determine suitability for recycling. As mentioned previously, the storage levels of hoist garages were frequently not designed to allow comfortable routine passage of erect humans. Clear
floor-to-ceiling heights are sometimes less than six feet. Ramped garages were usually designed for such passage and floor-to-ceiling heights tend to be greater. Clear floor-to-ceiling heights must meet minimum standards such as those given in Table 3.2 in order to be used as inhabitable spaces. The mean floor-to-ceiling height for all garages in Table 3.1 indicates that this is not always a problem. Where this clear height is measured to the bottom of a beam or tee, there is a bonus because for most of the floor area, that between the beams or tees, the floor-to-ceiling height exceeds that typically provided in current housing designed to satisfy minimum standards. Where the clear height is only slightly less than the required minimum at discrete infrequent points, it may be possible to obtain a variance. An associated problem, however, is the undesirability of such exposed ceilings. Finishing treatments are important.

A more common problem of restrictive existing floor-to-ceiling heights arises because mechanical services must be distributed throughout the building. Typically, this is accomplished in the space between the ceiling and the bottom of the floor above. The choice of individual air tempering units for the apartments that do not require large pipes and ducts can alleviate or avoid this problem. Ductwork necessary for the ventilation of corridors and public spaces can be managed as local conditions permit. Plumbing and exhaust from kitchens and baths can be stacked so that horizontal
Habitable Rooms 7'-6"
Halls within Living Units 7'-0"
Bathrooms 7'-0"
Public Corridors 7'-8"
Public Rooms 8'-0"
Sloping Ceilings Greater than 7'-6" for half the room, & Greater than 5'-0" for whole room.

Table 3.2 Minimum clear floor to ceiling heights required by HUD Minimum Property Standards, v. 2, Multifamily Housing.

<table>
<thead>
<tr>
<th>Building Code</th>
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<tr>
<td></td>
</tr>
<tr>
<td>(1938)</td>
</tr>
<tr>
<td>(1951)</td>
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<tr>
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</tr>
<tr>
<td>(1975)</td>
</tr>
<tr>
<td>(1978)</td>
</tr>
</tbody>
</table>

Table 3.3 Minimum uniformly distributed design live load for auto parking garages. Dates of the codes are given in parentheses. Full code titles are listed in the bibliography.
distribution is minimized. Electrical service requires little space and can be run through partitions or within a new topping. In cases where the floor-to-ceiling height is insufficient to permit the running of ducts, pipes, and conduit beneath the lowest point, it may be possible to accomplish most distribution between members and to run through them when necessary. Even if the location of reinforcement allows holes to be made in the concrete members, coring and cutting should not be extensive. Such operations are expensive. Structural integrity of the members must be maintained.

If it is determined that type of garage, its depth, and its floor-to-ceiling height do not preclude recycling, then the garage must be more closely analyzed in light of five clusters of considerations.

**Building Code Requirements**

This section does not purport to list and analyze all of the many building code provisions that are applicable to the recycling of a garage for residential use. Only those requirements which fundamentally influence the organization of the new use within the existing building or which determine general building limitations are discussed. This section refers throughout to The BOCA Basic Building Code /1978. Provisions of local codes will vary.

The extent to which the recycled garage must meet current building code requirements depends on the cost of
alterations as a percentage of the value of the existing
building. If the cost of alterations is less than fifty
per cent of the value of the building, only the portions
altered need meet the code requirements for new construction.
If the cost of alterations exceeds fifty per cent of the
value of the existing building, the entire building must meet
code requirements for new construction. Common sense and a
responsible attitude toward human safety suggest that the
radical change in use, from parking to housing, would re-
quire that the completed recycled building meet code require-
ments for new construction.

Specific requirements are principally determined by two
classifications--use group and type of construction. As a
multi-family dwelling having more than two dwelling units,
the recycled garage is a use group R-2 structure. Because it
is constructed of concrete the garage is classified as type 1,
fireproof construction. To insure that the completed re-
cycled building remains type 1 construction, all new con-
struction, structural and nonstructural, must meet proper
fire resistance requirements. (The classification as to type
of construction depends on the fire resistance ratings of the
various structural elements within the completed building.
It is possible, though not likely, that the concrete cover
of the reinforcement in main structural members is insuffi-
cient to afford the fire resistance rating required by type 1,
fireproof construction. It is possible, then, that the
garage would be of type 2A, noncombustible protected construction.)

Height and area limitations for the recycled building are given according to use group and type of construction. Multi-family residential (R-2) fireproof construction (type 1) is subject to no building code restrictions for height and area. (Multi-family residential (R-2) noncombustible protected construction (type 2A) may not exceed nine stories or 100 feet in height and 22,800 square feet in the area. The area limitation may be increased by excess street frontage or by the employment of an automatic fire suppression system. Note that basic area limitation is approximately equal to the median gross square footage for garages listed in Table 3.1.)

Urban parking garages are likely to be located within city fire districts. Only certain construction types are allowed within these districts. Type 1 is always permitted. Type 2A is usually permitted. Height and area limits may be contingent on location within a fire district. Other code requirements may be contingent on location also (e.g., width of fire separation, fire resistance of opening protectives, street encroachments).

Egress requirements are determined by use group classification. At least two remote exitways must be provided for each floor. (8) Maximum exitway access travel, typically through a fire protected passageway, is limited to 100 feet.
without fire suppression system and to 150 feet with such a system. Codes may allow a maximum length of exitway travel of 400 feet in buildings of unlimited area.

Minimum uniformly distributed design live loads are determined by particular use within the use group designation. Live loads for multi-family residential buildings are as follows:

- Private apartments: 40 p.s.f.
- Public rooms: 100 p.s.f.
- Corridors: 80 p.s.f.

Uniformly distributed live loads may be reduced as follows:

For live loads of one hundred (100) pounds or less per square foot, the design live load on any member supporting one hundred fifty (150) square feet or more may be reduced at the rate of eight-hundredths per cent (0.08%) per square foot of area supported by the members. The reduction shall exceed neither "R" as determined by the following formula, nor sixty (60) per cent:

\[ R = 23 \left(1 + \frac{D}{L}\right), \]

where

- R = reduction in per cent;
- D = dead load per square foot of area supported by the member; and
- L = design live load per square foot of area by the member.

The comparison of the new design live loads to those for which parking garages were typically designed is discussed in the next section.
Among the many other building code requirements that apply to the recycling of a garage, one deserves recognition. The recycled garage must provide handicap access "to all levels and areas used by the general public, employees, (and) persons visiting or on the premises for any reason. . . ." (12)

Specifically,

At least one (1) dwelling unit for every twenty-five (25) dwelling units or fraction thereof in use group R-2 (residential, multi-family) buildings shall be made accessible to physically handicapped persons. The dwelling units allocated for the physically handicapped shall be proportionally distributed throughout all types of units. Laundry and storage facilities shall be accessible from the barrier free units. Access to additional floors without public facilities is not required. (13)

Structural Considerations

The structure of the garage, as individual members and as integrated system, must possess sufficient strength to resist applied loads and must also be of sufficient stiffness to control deflections and cracking, which permits corrosion of reinforcements. The garage structure must perform adequately under the new use and any physical alterations.

The change in use affects design live loads. Additions to or alterations of the original building affect design dead loads. Lateral loads, too, may change with recycling. Additions to the overall building will affect seismic
response. An increase in mass will produce greater lateral loading. Infill construction can change the stiffness of the building and may help or hinder seismic response. Increasing the height of the original structure will change the fundamental period. An increase in height and installation of enclosure will affect the wind loading of the building. Alteration through selective demolition and through addition will affect the response of the system and its components.

As indicated in Table 3.1, parking garages tend to be squat structures—broad, deep, and short. In original form they are probably adequately designed and built to resist lateral loading due to earthquakes or wind. Even with the addition of several new stories, the recycled garage may possess sufficient strength to resist lateral loads with little or no alteration of the original structure. Major additions will require alteration of the original structure to support new gravity loads. Such alteration can be designed to strengthen the original structure to resist lateral loads as well. During minor structural alteration, care must be exercised to preserve the integrity of the original structure.

Obviously if there is serious concern that the recycled building can resist lateral loads, the capacity of the structure must be checked. However, the principal concern in a brief feasibility analysis of a garage recycling without major addition is the capacity to resist new gravity loads.
Foundation, column, wall, girder, beam, and slab all must possess strength sufficient to resist applied loads arising from the new use and physical alteration.

It is useful to make a simple comparison between the design live loads for the storage of automobiles and those required for multi-family residential use. Table 3.3 gives uniformly distributed design live loads as required by various building codes. Until the late 1960s the typical design live load for garages was 75 p.s.f., although minimum requirements of 100 p.s.f., or greater, did exist. From the late 1960s to the present, 50 p.s.f. has been the required minimum.

Minimum uniformly distributed live loads for the various uses of multi-family residential use group are given in the previous section. Based on the schematic designs of part IV (see Figure 4.4), it is reasonable to ascribe the following square footage percentages for the various sub-uses on a per floor basis:

- Apartments 40 p.s.f. 80%
- Balconies and Public Rooms 100 p.s.f. 10%
- Corridors 80 p.s.f. 100%

According to these assumed percentages, the average live loading over a floor of multi-family residential use is 50 p.s.f. This is no greater than recent minimum design live load requirements for automobile parking. It is two-thirds of the minimum design live load likely to have been
required for parking before the late 1960s. When reduced, as allowed by code, the design live loads for residential use are certain to be less than those for which the garage was designed. (Live load reduction is not allowed for parking use, except that the live load for columns may be reduced by up to 20%.)\(^{(14)}\) Therefore, parking garages generally, and those built before 1970 especially, should possess strength sufficient to resist applied live loads arising from residential use.

An increase in dead load, due to the addition of infill and finish construction, may offset the lower design live load arising from reuse of the garage as housing. Thus, the difference in total gravity load for original and new use depends also on the ratio of live load to dead load.

It is necessary to check the capacity of members in those cases where the new gravity load clearly exceeds the old (i.e., balconies, public rooms, and corridors). In such cases, analysis may show that the original structure, as designed and built, possesses adequate capacity to resist new loads. If calculated capacity based on accurate material strengths and current design practice is inadequate, the members can be modified to increase strength. Possible methods are discussed below. Variances in design loads may be granted by code administrators where appropriate. Engineers may use responsible judgment in deciding that actual capacity is in excess of calculated values and that loads
can be resisted with adequate margin of safety.

The difference between new and old overall gravity loading may allow the addition of new stories without strengthening of the original structure, provided that individual members are able to resist the new loads they must carry. For example, if original loads for parking were

\[
\begin{align*}
DL &= 150 \text{ p.s.f.} \quad LL = 75 \text{ p.s.f.} \quad \text{Total} = 225 \text{ p.s.f.}, \\
\end{align*}
\]

ew loads for residential use are

\[
\begin{align*}
DL &= 160 \text{ p.s.f.} \quad LL = 40 \text{ p.s.f.} \quad \text{Total} = 200 \text{ p.s.f.}, \\
\end{align*}
\]

and loads for additional stories are

\[
\begin{align*}
DL &= 110 \text{ p.s.f.} \quad LL = 40 \text{ p.s.f.} \quad \text{Total} = 150 \text{ p.s.f.}
\end{align*}
\]

then for each six existing stories, the difference between original use and new use, 225 - 200 = 25 p.s.f., will allow the construction of an additional story. Horizontal framing members will not be affected by this addition of stories, except if they are also part of the lateral-load resisting system which will now be subjected to greater earthquake loads because of an increase in self weight of the building. The further a vertical bearing member is from the additional construction, the better able it is to carry the new loading. For the foundation and lower-story columns, the loads from new construction effectively replace the loss of gravity loads due to change in use. However, columns in the existing
upper stories may not possess the capacity to carry the loads from new construction, which more than replace the loss in overall gravity loads due to change in use, unless they are strengthened. The ability to add new floors depends on the difference between new and original gravity loads and on the ratio of dead load to live load for the particular garage.

It may prove propitious to calculate the strength of typical structural members even if gross analysis indicates that new loads exceed original loads. Values that accurately reflect true material strengths and current analysis and design practices may yield calculated capacities well in excess of those for which the structure was originally designed. Older design practices tend to be conservative by present standards. However, it must be recalled that part of this conservatism was due to greater variability in material strengths. Tests to determine actual material strengths may be useful, if not necessary.

Where the strength of members is clearly insufficient, it is possible to alter the structure to increase strength. Methods of strengthening depend on the nature of the inadequacy, the type of structure, and the particular member. New members can be added. The deficient member can be replaced. Steel plates can be added to the bottom of beams and slabs. Steel plates can be added to the sides of beams. New concrete can be added to the bottom of beams to include additional reinforcement.
Making openings in the floor is an important concern in recycling parking garages. How this can be accomplished depends on the size of the opening and the characteristics of the floor construction. The behavior of the beams and slabs must be investigated with regard to strength and stiffness. Ascertainment of the location of reinforcement is necessary.

In either prestressed or reinforced concrete construction, it is possible to core or cut small openings necessary for the distribution of mechanical services. Care must be taken that the opening is not located in an area subject to exceptional local stresses. Too, principal reinforcement must not be disturbed.

Methods for making larger openings depend greatly on the original construction. Large openings can easily be made in reinforced concrete frame construction if the new edge of the slab occurs at or just beyond a beam edge. Where the new slab edges are free, it may be necessary to provide additional strength or stiffness with edge beams running parallel to existing beams or with header beams that frame into existing beams. Where openings larger than a single bay are required, beams themselves can be removed. Preservation of overall structural integrity must be maintained. Similar methods can be employed with flat slab construction. Column strips are treated as beams. Provision of additional stiffness at new edges will usually be required.
Making openings in precast, prestressed concrete construction is more difficult. Again, exact methods depend on opening size and type of construction. Whole elements can be removed. Infill can then be used to decrease the opening to the desired smaller size. Sections along the length of members can be cut out. The remaining pieces can then be headed-off to transfer loads to adjacent members. Examples of this type of opening construction are given in part IV.

Posttensioned construction exhibits problems similar to precast. Because it is cast in place, actual separate elements do not exist. If regarded as such, however, then methods similar to those used for precast prestressed construction can apply.

Proper control of deflections in a recycled garage is important for several reasons. Excessive deflections can be unsightly and can cause false concern about strength. Excessive deflections can transfer loads to nonstructural construction, causing damage to interior partitions and exterior enclosure. This redistribution of loads may adversely affect the behavior of the building under dynamic lateral loading. Deflections can exceed standard tolerances in fitting infill to the structure. Unusual and more costly methods of construction would be required. Excessive deflections indicate floor flexibility that is uncomfortably "bouncy" to occupants. Finally, excessive deflections may indicate cracking of an extent that will allow undesirable
corrosion of reinforcement.

Traditionally, limits for deflection are given as fractions of span length and are contingent upon use of the structure. Deflection is not to exceed \( \frac{L}{480} \) for "roof or floor construction supporting or attached to non-structural elements likely to be damaged by large deflections." \(^{(15)}\) Where deflections are not likely to damage nonstructural elements, deflections up to \( \frac{L}{240} \) are allowed. Because parking garages are not intended for human occupancy it is likely that they are designed to meet only less restrictive limits. It is necessary to check actual deflections in the garage, and to calculate deflections due to new loading. If excessive deflections cannot be avoided, they can at least be acknowledged and provided for in design and new construction.

Deflection problems are most acute in recycling newer garages which have longer-span structures and in which assumed original design live loads are equivalent to the overall design loads required by the new use. Control of deflection causes few problems in recycling older garages which are of shorter span and which assumed original design live loads significantly greater than those required by residential use.

**Nonstructural Construction**

The element of parking garages that is most obviously lacking in order to complete recycling is enclosure. Beyond
its formal function, enclosure affords necessary weather protection for the building. The importance of enclosure to the energy performance of the building is noted below.

In short structures the enclosure can support itself and can be tied to the superstructure for lateral support only. Most garages, as they exist or are added to, are of a height too great for this type of enclosure. The need to provide new foundations discourages the use of self supporting systems in a recycled building. Two types of enclosure or their combination are suitable.

Enclosure can be hung outside the structure. A curtain wall is such enclosure. This method has several advantages. The enclosure protects the entire structure from weather and attendant corrosion. Thermal differential between portions of the structure is minimized. Such enclosure is especially amenable to the use of prefabricated construction. The partial closure that exists on many garages may provide the basic detailing necessary for the attachment of the new system. Finally, such construction comprises an independent system which can easily allow movement of the structure. This independence decreases the possible adverse interference with or damaging consequences of the behavior of the building under dynamic lateral loading. Several disadvantages must be observed. Details of attachment are complicated and construction of them in an existing building can be more so. The installation of prefabricated elements requires the use
of expensive handling equipment. The sealing of such construction from the outside may require extensive scaffolding. Balconies and devices for sun shading must be added to the enclosure.

Enclosure can also be constructed within the structure, between floors. Such enclosure allows construction to be of common materials that are easily handled and assembled by workers. If enclosure occurs a sufficient distance inside the edge of the floors, many benefits derive. Construction can easily be worked from the outside without the need for scaffolding or expensive equipment. Outdoor balconies are created which provide sun shading. Where the depth of the building is great, balconies decrease the effective depth of the apartments. When a pitched topping on the balcony is combined with an integral curb at the enclosure, easy waterproofing is achieved. Attachment to the structure is facilitated, since the enclosure bears directly on the floors. Formally, such construction allows the structure to read from the outside. Two disadvantages follow. First, a portion of the structure is exposed to the weather. Thermal differential will develop; corrosion protection must be ensured. Second, enclosure is less independent of the structure and is more likely to affect the behavior of the building under dynamic loading. This inherent disadvantage can be overcome through proper design and detailing.
The energy performance of the building is a second important aspect of nonstructural construction. Control of heat transmission through the building envelope is achieved through the proper design of enclosure and selection of insulating construction. Though the orientation of the original structure is fixed, the design of additional construction and selective demolition can be utilized to control gross solar gain. Local sun shading can be accomplished by balconies and other internal and external devices. Active solar systems for space heating or hot water can be fitted to the existing structure and can be incorporated into the design of new construction. The judicious selection of heating and air conditioning systems is similar to that for new buildings since no old system, or remnants of such, exist in a parking garage. Limitations on the selection of a system concern distribution, as discussed previously.

Interior infill must be designed and detailed so as not to interfere with the structural performance of the building. Finish construction for recycled concrete garages is important if only because of its necessity and relative cost. Proper treatment of the exposed structure must consider the comfort of occupants. Sound characteristics and aesthetic acceptability are two such criteria.

The architects hope that with imaginative lighting and decoration the ceiling pattern can be made attractive. (16)
Mechanical Systems

It is not within the purview of this thesis to design mechanical systems or to recommend the use of particular types for a recycled parking garage. It is relevant to note the difficulties presented in the distribution of systems within an existing structure that was not designated to accommodate such use. Openings are not provided. Floor-to-ceiling heights usually do not allow space for a plenum or for the distribution of large pipes and ducts.

The provision of heating, ventilation, and air conditioning (HVAC) for apartments can be accomplished with individual heat pumps or fan coil units that need only small diameter supply pipes. HVAC for interior public spaces requires some ductwork. The creation of necessary openings for this distribution can be problematic.

Plumbing requires only small openings. Uses requiring plumbing can be stacked so that only vertical distribution is needed.

Electrical service requires wire and conduit of smaller diameter that can be run through new partitions, new topping, or ceiling spaces.

The considerations in recycling, which have been generally discussed in this part, are used in the next part to study the suitability of recycling a particular urban parking garage.
part IV: ANALYSIS OF WEST GARAGE

In this part, the feasibility of recycling the West Garage, at the Massachusetts Institute of Technology in Boston, into housing is examined. The brevity, assumptions, and approximate analytical methods of this study are justified by the need for basic information with little investment of time and money. Full, detailed analysis would follow the decision to recycle based on this basic information.

The West Garage is used as an example for several reasons. It is located in an urban area. It is constructed of reinforced and precast, prestressed concrete. Most importantly, analyzing the feasibility of recycling the garage for residential use illustrates issues, problems, and solutions that arise in examining other garages. Finally, this garage is presented because it was possible to obtain complete construction documents for it. Even for garages only twenty or thirty years old, the location and procurement of complete information can be difficult.

The West Garage is not offered as an average or a typical parking garage. The problems and, especially, the
solutions that follow are particular to this building. Similar problems requiring different solutions will develop for other garages. The choice of this garage does not suggest that it will be, or should be, either abandoned or recycled.

**Description**

Built in 1963 for the Massachusetts Institute of Technology, the West Garage features five level floors connected by internal ramps. Basic architectural and structural description is given in Figure 4.1. In plan the garage measures 90 by 416 feet. Floor-to-floor height is 10'-0". Typical floor-to-ceiling height is 7'-8" under girders, and 8'-1½" under tee stems. Continuous cast-in-place concrete girders span in three lines in the long direction of the garage. Precast, prestressed concrete double tees run transversely and are let in to the cast girders at each end. An average of 4½" of concrete is cast on top of the butting tee flanges. Shear stirrups extending from the stems, and roughened top surface of the flanges insure sufficient bonding to develop full composite action between the cast-in-place topping and the precast tees.

**Simple Indicators**

The garage does not have any of the three characteristics that would quickly and simply preclude its recycling for residential use. Except for the short run of ramps,
Figure 4.1 Plan and sections of West Garage, showing existing conditions.
the floors are level. Depth measures 90 feet. Though greater than the optimum building depth for housing, 60-70 feet, it is much less than the depth of many garages. The lowest existing floor-to-ceiling height is two inches greater than the minimum required. The prevailing floor-to-ceiling height, 8'-11/2", is generous.

Building Code Requirements

The scheme for recycling the West Garage for residential use is illustrated in Figure 4.2, which shows the organization for a typical floor. Apartments are double loaded about a center corridor. The width of the corridor is exaggerated in order to include exterior storage and to allow the actual circulation to occur on either side of the columns. Balconies occupy approximately six feet of each longitudinal exterior edge. Ramps are replaced by extensions of the intermediate floor level. The basement level, because it is 6 feet below grade, is retained for use as parking.

Proper egress is provided by using one of the existing fire stairs, by constructing a new stair tower in a more advantageous location to replace the other existing stair, and by constructing a main stair in the area where new floors replace the ramps.

Because of its all-concrete construction, the garage is a type 1, fireproof building. If new construction is designed to meet required fire ratings, the recycled building
Figure 4.2 Scheme for recycling typical floor of West Garage.
can retain such classification. Area and height are not limited by code in type 1 construction. As noted below, however, the height is controlled by the capacity of the existing columns and foundation.

Figure 4.3 shows schematic designs for typical apartments. The wider central corridor and the balcony decrease the depth of the apartment. Portions of the corridor can be used for private storage outside the apartment. Balconies are a pleasant amenity.

**Structural Considerations**

The structural analyses that follow are not exacting. They employ approximate methods and make many assumptions in order to provide information quickly.

The original design live load for the garage was 60 p.s.f. The applicable design live loads for residential use are listed in part III and are shown in Figure 4.2. Factored and unfactored design loads for original and new use are summarized in Table 4.1a - 4.1e.

Because the height of the garage is small compared to either of its horizontal dimensions, it is assumed that the lateral loading due to earthquake is more important than that due to wind, despite the increase in projected area subject to wind loading resulting from the addition of enclosure. The per-floor unfactored dead load can be figured from Tables 4.1d and 4.1e as the total dead load
Figure 4.3 Plan and section of typical apartment in recycled West Garage.
### Table 4.1a Loading for typical composite double tee in West Garage according to use.

<table>
<thead>
<tr>
<th></th>
<th>New Use: Housing</th>
<th>Old Use: Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dead Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self Wt.</td>
<td>$3.23 \text{ ft}^2 \times 150 \text{ lb/ft}^3 = 484.4 \text{ lb/ft}$</td>
<td>$3.23 \text{ ft}^2 \times 150 \text{ lb/ft}^3 = 484.4 \text{ lb/ft}$</td>
</tr>
<tr>
<td>Partitions</td>
<td>$20 \text{ lb/ft}^2 \times 5 \text{ ft} = 100 \text{ lb/ft}$</td>
<td></td>
</tr>
<tr>
<td>Misc. DL(^a)</td>
<td>$5 \text{ lb/ft}^2 \times 5 \text{ ft} = 25 \text{ lb/ft}$</td>
<td>$5 \text{ lb/ft}^2 \times 5 \text{ ft} = 25 \text{ lb/ft}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$609.4 \text{ lb/ft}$</td>
<td>$509.4 \text{ lb/ft}$</td>
</tr>
<tr>
<td>Factored (x 1.4)</td>
<td>$853.1 \text{ lb/ft}$</td>
<td>$713.1 \text{ lb/ft}$</td>
</tr>
<tr>
<td><strong>Live Load(^b)</strong></td>
<td>$(47.5 \text{ lb/ft}^2 \text{ red. by 16%}) \times 5 \text{ ft} = 200 \text{ lb/ft}$</td>
<td>$60 \text{ lb/ft}^2 \times 5 \text{ ft} = 300 \text{ lb/ft}$</td>
</tr>
<tr>
<td>Factored (x 1.7)</td>
<td>$340 \text{ lb/ft}$</td>
<td>$510 \text{ lb/ft}$</td>
</tr>
<tr>
<td><strong>DL + LL (factored)</strong></td>
<td>$1,193 \text{ lb/ft}$</td>
<td>$1,223 \text{ lb/ft}$</td>
</tr>
</tbody>
</table>

**Notes:**

\(a\) Accounts for miscellaneous construction in both new and old use (e.g., pipes, ceilings, curbs, and rails).

\(b\) Live load for housing is reduced according to procedure quoted in part III, Building Code Requirements. Live Load for parking cannot be reduced except for a maximum 20% reduction allowed for columns.

\(c\) Uniformly distributed load equivalent to exact loading shown in Figure 4.5.
Table 4.1b Loading for typical cast-in-place interior girder in West Garage according to use.

* See Table 4.1a for notes.
<table>
<thead>
<tr>
<th></th>
<th>New Use: Housing</th>
<th>Old Use: Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dead Load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self Wt.</td>
<td>$7 \text{ ft}^2 \times 150 \text{ lb/ft}^3$</td>
<td>$7 \text{ ft}^2 \times 150 \text{ lb/ft}^3$</td>
</tr>
<tr>
<td></td>
<td>= 1,050 lb/ft</td>
<td>= 1,050 lb/ft</td>
</tr>
<tr>
<td>Tee</td>
<td>$(609.4 \text{ lb/ft} \times 20 \text{ ft})/5 \text{ ft}$</td>
<td>$(509.4 \text{ lb/ft} \times 20 \text{ ft})/5 \text{ ft}$</td>
</tr>
<tr>
<td></td>
<td>= 2,437.5 lb/ft</td>
<td>= 2,037.5 lb/ft</td>
</tr>
<tr>
<td>Partitions</td>
<td>$20 \text{ lb/ft}^2 \times 3 \text{ ft}$</td>
<td>$5 \text{ lb/ft}^2 \times 3 \text{ ft}$</td>
</tr>
<tr>
<td></td>
<td>= 60 lb/ft</td>
<td>= 15 lb/ft</td>
</tr>
<tr>
<td>Misc. DL*</td>
<td>$5 \text{ lb/ft}^2 \times 3 \text{ ft}$</td>
<td>$5 \text{ lb/ft}^2 \times 3 \text{ ft}$</td>
</tr>
<tr>
<td></td>
<td>= 15 lb/ft</td>
<td>= 15 lb/ft</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3,562.5 lb/ft</td>
<td>3,102.5 lb/ft</td>
</tr>
<tr>
<td>Factored (x 1.4)</td>
<td>4,987.5 lb/ft</td>
<td>4,343.5 lb/ft</td>
</tr>
</tbody>
</table>

|                  |                  |                  |
| **Live Load**    |                  |                  |
| (47.5 lb/ft² red. by 60%) |                  |                  |
| $19 \text{ lb/ft}^2 \times 23 \text{ ft}$ | $60 \text{ lb/ft}^2 \times 23 \text{ ft}$ |
|                  | = 437 lb/ft      | = 1,380 lb/ft    |
| Factored (x 1.7) | 742.9 lb/ft      | 2,346 lb/ft      |

| **DL + LL (factored)** | 5,730.4 lb/ft | 6,689.5 lb/ft |

Table 4.1c Loading for typical cast-in-place exterior girder in West Garage according to use.

* See Table 4.1a for notes.
<table>
<thead>
<tr>
<th></th>
<th>New Use: Housing</th>
<th>Old Use: Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dead Load (per floor)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self Wt.</td>
<td>4.95 ft² x 150 lb/ft³ x 7.5 ft = 5.6 kips</td>
<td>4.95 ft² x 150 lb/ft³ x 7.5 ft = 5.6 kips</td>
</tr>
<tr>
<td>Girders</td>
<td>6,562.5 lb/ft x 33.5 ft = 219.8 kips</td>
<td>5,672.5 lb/ft x 33.5 ft = 190.0 kips</td>
</tr>
<tr>
<td>Total</td>
<td>225.4 kips</td>
<td>195.6 kips</td>
</tr>
<tr>
<td>Factored (x 1.4)</td>
<td>315.6 kips</td>
<td>273.8 kips</td>
</tr>
</tbody>
</table>

| **Live Load (per floor)**   |                  |                  |
| (47.5 lb/ft² red. by 60%)   | (60 lb/ft² red. by 20%)  |
| 19 lb/ft² x 44.5 ft x 33.5 ft = 28.3 kips | 48 lb/ft² x 44.5 ft x 33.5 ft = 71.5 kips |

Factored (x 1.7) 48.1 kips 121.6 kips

| **DL + LL (factored)**      |                  |
|                            | 363.7 kips       |
|                            | 395.5 kips       |

Table 4.1d  Loading for typical cast-in-place interior column in West Garage according to use. Because of large tributary areas, maximum rate of live load reduction is achieved in one floor of loading. Loading at any level can be figured by simple addition of loads for floors above. * See Table 4.1a for notes.
Table 4.1e Loading for typical cast-in-place exterior column in West Garage according to use. Because of large tributary areas, maximum rate of live load reduction is achieved in one floor of loading. Loading at any level can be figured by simple addition of loads for floors above.
* See Table 4.1a for notes.

<table>
<thead>
<tr>
<th>Dead Load (per floor)</th>
<th>Old Use: Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Self Wt.</strong></td>
<td>2.64 ft² x 150 lb/ft³ x 7.5 ft = 3.0 kips</td>
</tr>
<tr>
<td><strong>Girders</strong></td>
<td>3,562.5 lb/ft x 33.5 ft = 119.3 kips</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>122.3 kips</td>
</tr>
<tr>
<td><strong>Factored (x 1.4)</strong></td>
<td>171.2 kips</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Live Load* (per floor)</th>
<th>(47.5 lb/ft² red. by 60%)</th>
<th>(60 lb/ft² red. by 20%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 lb/ft² x 23 ft x 33.5 ft = 14.6 kips</td>
<td>48 lb/ft² x 23 ft x 33.5 ft = 37.0 kips</td>
<td></td>
</tr>
<tr>
<td><strong>Factored (x 1.7)</strong></td>
<td>24.8 kips</td>
<td>62.9 kips</td>
</tr>
</tbody>
</table>

| DL + LL (factored) | 196.0 kips | 212.6 kips |
per column times the number of columns in a floor. Thus, the per-floor dead load for residential use is

\[(11 \times 225.4 \text{ kips}) + (22 \times 122.3 \text{ kips}) = 5,170 \text{ kips.}\]

The per-floor dead load for parking use is

\[(11 \times 195.6 \text{ kips}) + (22 \times 106.9 \text{ kips}) = 4,503.4 \text{ kips.}\]

If the total weight of the recycled building is figured as four stories plus one-quarter story to account for a light weight roof structure (= 2,972 kips), and the total weight of the original garage is figured as four stories (= 18,014 kips), then the total weight of the recycled building is 22% greater than that of the original garage. It is assumed that, as designed and built, the moment resisting frame can adequately resist lateral loads generated by an earthquake acting on the original garage. Because of the modest difference in total weight between the recycled and the original building, it is further assumed that the same moment resisting frame can adequately resist those lateral loads generated by an earthquake acting on the recycled building. As discussed below, increasing the height by adding new stories would necessitate modification of the structure to carry additional gravity loads. The increase in height and weight would change the seismic response of the building, and would necessitate the modification of the lateral load resisting system as well. Shear walls, as partitions between
apartments, can provide additional resistance if, under closer analysis, the original structure is found to be inadequate, or if the weight of the building is increased greatly.

Tables 4.1a-4.1e show that the overall gravity loading per floor is similar for new and original uses. Factored gravity loads carried by tees under residential use are 2% less than those carried under parking use. Because this difference is slight and because the live loading is not uniform, the capacity of typical tees is checked below. Factored gravity loads carried by typical exterior and interior girders under residential use are 15% and 14%, respectively, less than those carried under parking use. Factored gravity loads carried by typical exterior and interior columns under residential use are 8% less than those carried under parking use. Similarly, new gravity loads carried by typical foundations (under columns) are 8% less than original gravity loads.

Because the West Garage is only four stories in height, the difference between new and original gravity loads for the exterior columns,

\[
\frac{(196.0 \text{ k} - 212.6 \text{ k})}{(23 \text{ ft} \times 33.5 \text{ ft})} = 21 \text{ p.s.f.,}
\]

and for the interior columns,

\[
\frac{(363.7 \text{ k} - 395.5 \text{ k})}{(44.5 \text{ ft} \times 33.5 \text{ ft})} = 21 \text{ p.s.f.,}
\]
does not accumulate to the degree necessary to allow loads from the addition of a new story. At the foundation of an exterior column, the "free" capacity due to recycling is only 84 p.s.f. (66.4 kips). This is much less than would be added by the construction of one new story. New stories cannot be added without considerable strengthening of all columns and foundations. Indeed, upper columns may only just be able to carry the additional loads from a new roof.

The double tees in combination with the cast-in-place topping act as slab and framing for the floor. Figure 4.5 shows that the residential gravity loading for a typical tee varies along its length, and is different than the gravity loading for parking. Consequently, the double tee is checked for strength in flexure and shear. Figure 4.4 describes the double tee composite member and lists relevant properties. The following analysis assumes simple supports and neglects reinforcement in the cast-in-place slab.

First, the capacity of the double tee in flexure is calculated. Because $f_{pe}$ is greater than $0.5f_u$, the following equation can be used to determine $f_{ps}$:

$$f_{ps} = f_u (1 - 0.5p \frac{f_u}{f_c})$$

(ACI 18-3)

provided that $f_{ps}$ exceeds neither $f_{py}$ nor $(f_{pe} + 60,000)$. 
Figure 4.4 Configuration and properties of typical precast, prestressed double tee in West Garage.

\[
\begin{align*}
&b = 60 \text{ in} \\
&b_w = 2 \times 4.75 = 9.5 \text{ in} \\
&A_g = 465 \text{ in}^2 \\
&I_g = 11,978 \text{ in}^4 \\
&A_p = 1.08 \text{ in}^2 \\
&A_v = 0.196 \text{ in}^2 \\
&f_{c,p} = 5,500 \text{ psi} \\
&f_{c,\text{cip}} = 3,000 \text{ psi} \\
&f_y = 20,000 \text{ psi} \\
&f_u = 250,000 \text{ psi} \\
&w_c = 150 \text{ pcf} \\
&E_c = 4,227,000 \text{ psi} \\
&C_u = 2.35 \\
&E_p = 27,000,000 \text{ psi} \\
&f_{p1} = 166,700 \text{ psi} \\
&f_{pe} = 131,700 \text{ psi}
\end{align*}
\]
Figure 4.5 Capacity and ultimate values in bending and in shear for typical double tee in West Garage.
In this case the latter limit controls, and \( f_{ps} \) is taken as equal to 191.7 k.s.i. The reinforcement index

\[
\rho_p \frac{f_{ps}}{f_c} = 0.0809,
\]

is less than 0.30, which indicates that the tees are under-reinforced. Thus, according to the ACI code, the following equation will accurately predict strength in flexure:

\[
M_n = A_p f_{ps} (d - \frac{a}{2}), \text{ where } a = \frac{A_p f_{ps}}{0.85 f_c b} \quad \text{(Nilson 3.23)}
\]

Shear capacity is provided both by concrete and reinforcement. According to the ACI code, where \( f_{pe} \) is not less than 0.40\( f_u \), the shear strength contributed by the concrete is given by

\[
V_c = (0.6 f'_c + 700 \frac{u}{M_u}) b_w d. \quad \text{(ACI 11-10)}
\]

\( V_c \) need not be taken less than \( \sqrt{2} f'_c b_w d \), nor may it be taken greater than \( \sqrt{5} f'_c b_w d \). Shear strength provided by reinforcement perpendicular to the axis of the member is given by

\[
V_s = \frac{A_v f_d}{s}, \quad \text{(ACI 11-17)}
\]

where \( s = \) spacing of reinforcement in inches.

Shear capacity is then given by \( V_c + V_s \).

Figure 6 compares ultimate moment \( (M_u) \) and ultimate shear \( (V_u) \), as produced by factored loads, to factored strength of the typical composite double tee in bending \( (\phi M_n) \) and in shear \( (\phi V_n) \). Strength of the tee is adequate.
In summary, preliminary analysis suggests that the original structure of the garage has sufficient strength to resist lateral and gravity loads arising from residential use. The building cannot increase in height without modification of the structure to resist added lateral and gravity loads.

The ACI code requires that, in the design of flexural members, deflections do not exceed permissible values given as fractions of span length (see part III, Structural Considerations). These limitations on calculated deflections are intended to assure stiffness and levelness of horizontal surfaces that are adequate for human comfort. Also, these limitations ensure that no damage is caused to nonstructural construction by excessive deflections of the structure.

Because the West Garage was constructed over fifteen years ago, it can be assumed that long term deflections of girders and tees have been achieved, and that these deflections are stable under the gravity loads due to use as parking. The feasibility study of the recycling of the garage is concerned with the possible change in deflections due to the change in use from parking to housing. If the new service-live-load for interior girders is taken as (15 p.s.f. x 44.5 ft = 667.5 lb/ft), and if the original service-live-load for interior girders is taken as (30 p.s.f. x 44.5 ft = 1,335 lb/ft), then the increase in unfactored dead load due to recycling (890 lb/ft, from Table 4.1b) is offset by this decrease in service live load (667.5 lb/ft). Similar analysis for
exterior girders will show that the service load effecting
deflections of all girders increases by 3% because of re-
cycling. In the same manner, the service load effecting de-
flections of tees can be shown to increase 4% because of re-
cycling. These small changes in service loads indicate that
deflections will not change significantly because of recycling
of the garage.

It can be assumed that as designed and built, the de-
flections of girders and tees do meet the less restrictive
limitation of \( \frac{L}{240} \), and that deflections do exceed the maximum
permissible value of \( \frac{L}{480} \) applicable where damage to non-
structural construction is likely. Measurements show that
the typical deflection of girders is approximately 1-3/8",
which is less than \( \frac{L}{240} = 1.675" \), and is greater than \( \frac{L}{480} = 0.837" \).

Long term deflection of the composite double tees can
be calculated by the formula

\[
\Delta = -\Delta_{pe} - \frac{\Delta_{pi} + \Delta_{pe}}{2} + (\Delta_{o} + \Delta_{d})(1 + C_u) + \Delta_l \quad \text{(Nilson 9.10)}
\]

where

- \( \Delta_{pi} \) = midspan deflection due to initial prestress,
- \( \Delta_{o} \) = midspan deflection due to self weight,
- \( \Delta_{pe} = \frac{\Delta_{pi} e}{p_i} \)
- \( \Delta_{d} \) = immediate deflection at midspan due to dead
  load
\[ \Delta_l = \text{immediate deflection at midspan due to live load}, \]
and
\[ C_u = \text{assumed equal to 2.35}. \]

The various partial deflections are found using equations from elastic theory. The gross moment of inertia is used in these equations because the composite section remains in compression under service loading and the section is assumed uncracked. Using these equations the double tee is found to exhibit 2.06" in camber. Measurements along the bottoms of tees indicate a typical camber of approximately \( \frac{1}{2} \)".

The seriousness of the violation of the permissible limit where nonstructural construction is likely to be damaged by deflections is mitigated by two observations. First, the camber in the tees exists only in the soffits; floors were leveled with the cast-in-place topping. Though there is likely to have been some additional deflection of this surface since construction, these small additional deflections occur over a span of 40 feet, and are not significant. Also, floors in the recycled building can be finish leveled by a taper screed final topping. Second, long term deflections have been achieved, and they will change little during the remaining life of the building. Insignificant change in deflection will result from the small change in gravity loading due to recycling. These stable, existing deflections can be "built in", provided that new construction allows for
some movement.

In summary, the motives for the control of deflection have been satisfied. Nonstructural damage is avoided. New construction can be designed and built to account for the stable, existing long-term deflections and to allow for small additional variations. Levelness is ensured by a finish topping poured over this stable surface. Adequate stiffness can be confirmed by physical inspection of the structure.

(In fact, there is no reasonable way to modify the existing structure to meet the more restrictive permissible deflection. The camber of the tees can be decreased by increasing the uniform dead load through the addition of a thick second topping, for example. Such an increase in dead load would soon exceed the capacity of the girders. Too, this represents a wasteful use of material. Deflections of the girders can be decreased by increasing their stiffnesses or by decreasing their spans. The increase in stiffness cannot be easily achieved. Floor-to-ceiling clearance under girders precludes the addition of reinforcement and concrete to the bottoms of members. Proper attachment of steel to the sides or bottoms would be difficult. The addition of intermediate columns would require the construction of new foundations.)

Small openings for pipes, wires, and ducts can be cut or cored through sections of the floor between the tee stems provided that primary reinforcement is not seriously
affected. Larger openings can be made by cutting out a section along the length of a double tee and heading off the cut ends so that the loads are transferred to adjacent tees. Figures 7a-7e show the ultimate values for shear and bending that are induced in adjacent tees by the creation of openings of various lengths located in various places along the span of the tees. These studies indicate that as the length of the opening is increased, and as the distance of the opening from midspan increases, the values for ultimate moment and shear decrease, and are more likely to be less than the factored capacity of the adjacent tees. The concrete header that distributes the load to the adjacent tees must be designed so that the load is carried to both stems. If the load is carried to only one stem of the pair, torsional rotation of the tee is possible. If the header is sufficiently stiff and is securely attached to the side of the adjacent stem, such rotation can be controlled. Additionally, the cast-in-place slab will help to prevent this rotation by binding the tees together. Openings wider than one double tee will require the additions of bearing members such as columns or walls, to support the cut ends of truncated members.

Nonstructural Construction

Nonstructural construction is important principally in its relation to the structure. As shown in Figure 4, the
Figure 4.6a Bending moment and shear induced in adjacent double tees by creation of opening in existing floor construction of West Garage. Cut ends are headed off to adjacent members. Factored loads (dead load and reduced variable live load) for residential use are replaced by equivalent uniformly distributed load. Transferred load from each cut section is increased by 2.5 ft x 1.075 k/ft, to account for additional dead load of header beams.
Figure 4.6b Bending moment and shear induced in adjacent double tees by creation of opening in existing floor construction of West Garage.
Figure 4.6c Bending moment and shear induced in adjacent double tees by creation of opening in existing floor construction of West Garage.
Figure 4.6d Bending moment and shear induced in adjacent double tees by creation of opening in existing floor construction of West Garage.
Figure 4.6e Bending moment and shear induced in adjacent double tees by creation of opening in existing floor construction of West Garage.
enclosure is set back from the outside edge to create a balcony, to ease construction, and to provide sun shading. This enclosure must be constructed to allow movement between itself and the structure due to thermal expansion and due to variable deflections. These joints must also be water and air tight. Similarly, the interior infill partitions must allow for movement of the structure. The simultaneous maintenance of air-tightness is important to afford adequate sound privacy, especially between apartments. This infill must be constructed to offer the fire rating required by the desired construction classification. Finally, the infill partitions must be designed to not interfere with the load bearing systems, both gravity and lateral, if such interference is not desired. If partitions are to assist in resisting loads then they must be designed to do this properly, too.

Mechanical Systems

The section in Figure 4 shows the important considerations regarding the mechanical services. Individual air handling units at the outside wall service the apartments. If kitchens and bathrooms are stacked, ducts from exhaust fans and plumbing can be run vertically through small openings in the floor. The ductwork necessary for the ventilation of the corridors and public spaces is more troublesome. Location in the ceilings is constrained by minimum headroom
Finally, this analysis of the West Garage returns to some architectural ruminations. The width of the apartments is essentially fixed by minimum—if not reasonable—room widths and the need for natural light. The depth of the apartments is fixed by the overall dimension of the building. This depth is decreased somewhat by the balconies and the wide center corridor. Nevertheless, the apartments are of much greater square footage than is usually obtained in an ideal apartment building of 60-70 foot depth. This excess square footage, not to mention that "wasted" in the wide corridor, represents an inefficient use of space. In turn, this represents an inefficient use of construction money which gives a greater unit cost. However, spaciousness also follows from this inefficiency. There is no guarantee of proper and beneficial design of this "extra" space. It can occur as always-coveted, always-insufficient storage. It can also be used to create an openness and connectedness that will more than offset the dimly lit, cavernous quality of the back of the apartment and the disquieting sensation of living in a former auto garage.
The primary conclusion that can be drawn from the preceding discussion is that the fundamental suitability of a particular parking garage for recycling into housing can be determined simply and quickly by considering its type, its overall dimensions—especially its depth—and its typical floor-to-ceiling height. If none of these three characteristics precludes recycling, then further consideration concerns the identification of particular architectural and structural problems and the discovery and selection of appropriate solutions to these problems. As is true in most ventures, once commitment is made to a particular course of action, no obstacles are found to be insurmountable. Once it is determined that recycling of a garage is not precluded, problems are defined and the effectiveness of various solutions—both in terms of cost and in terms of benefit to users—is assessed.

A caveat concerning the development of the recycling scheme is that it would not seem to be effective to add or to modify the garage to such an extent that major alteration
of the original structure is necessary. For example, only that number of new stories should be added that can be accommodated by the reserve capacity of columns and foundations, which is created by the difference between new and original gravity loads or as exists because of the conservative nature of the original structural design. Addition of new stories in excess of this number will require costly strengthening of the structure. Again, for example, the height and weight of the building should only be increased to the extent that the existing lateral-load resisting system is still effective without modification or with modification that can easily be accomplished. The addition of shear walls in a moment resisting frame can augment the capacity of the structure with little expense. In contrast, the modification of connections in order to increase ductility or fixity would be expensive, if not impractical.

Although there is no definite age that divides the types, it seems that "early" garages are better suited to recycling than are "late" garages. Based on the modest observation of many garages that was necessary for the preparation of this thesis, it is suggested that garages built until the early 1960s can be classified as "early", and that those built since then, especially those build since the late 1960s, can be classified as "late".

Early garages demonstrate many advantages for recycling. First, few early garages are of the ramped-floor type which
usually precludes recycling. Most garages have full- or split-level floors connected by discrete ramps. Very early garages are frequently of the hoist type, where the hoist-way can easily be converted to a desirable interior lightwell. Second, the floor-to-ceiling heights in early garages are greater than those produced in late garages by the overriding concern for efficient vertical stacking. Third, the shorter span of flexural members in early garages facilitates modest, local alteration of the structure which is often architecturally necessary. Fourth, the greater original design live-loads of early garages guarantee that the structure can accommodate the gravity loads of the new use. Fifth, the conservative structural design of early garages often results in members that, under modern methods of analysis, are found to have capacity great enough to accommodate significant increases in loading. Also, tests may show actual material strengths much greater than those assumed in the original design, especially for concrete. This, too, would indicate capacities greater than designed, and would allow an increase in loading. Sixth, flexural members in early garages have achieved long-term deflections. Such stable structural configurations facilitate infill construction.

Disadvantages of early garages must be noted also. First, the shorter spans of flexural members lessen the allowed reduction of live load, which is based on the area supported by the member. Though this loss of reduction will
probably not affect the capacity of members to carry loads due to new use, it will limit the ability to add new stories to the garage. Second, the benefit of the difference between the greater original live load and the lesser new live load depends on the ratio of dead load to live load. The greater dead load of early garages, due to their conservative and inefficient structures, causes this decrease in design live load to be insignificant in overall change in gravity loads. Too, this decrease in design live load may be offset by the increase in dead load due to infill construction. Third, although the strength of materials in early garages may be found to be greater than that assumed, the low reliability of these values may offset this gain. Fourth, the stability of long-term deflections in early structures is predicated on the maintenance of similar loading. Great changes in dead load or great variations in live load will change deflections immediately and in the long term. Finally, the acquisition of full, accurate design and construction documentation and of complete information on the history of uses and physical alteration is often difficult, if not impossible. The absence of such information necessitates costly measurement and testing, or requires conservative and inefficient design assumptions.

It is the author's opinion that the advantages outweigh the disadvantages. Early garages are better suited to recycling. As always, the test of this assertion, and its
value, is made in the examination of particular buildings. However, the above enumeration is useful as an assessment of the relative importance of the "considerations" of parts III and IV. Too, the above enumeration demonstrates succinctly that the determination of suitability for recycling and the development of the recycling scheme is a ragout of trade-offs. One strives for good taste born of the proper selection and balance of competing flavors.

Finally, this thesis briefly addresses the desirability of recycling a parking garage from the perspective of a person who would inhabit such a hybrid.

Compared to what is possible in housing, the double-loaded schemes likely to develop in the efficient recycling of parking garages are quite pedestrian. The strength of the simple stacked-floor configurations of the garages and the penurious effort to control the cost of recycling lead to the straightforward packing of apartments into repetitive layers.

Compared to what is currently offered in new construction, recycled garages can show some advantage. Apartments are almost certain to be more spacious because of the greater building depth. Though absolute floor-to-ceiling clearances may be low, the overall apartment height is likely to be greater than that commonly provided in new housing. The column spacing designed for parking may interfere enough with the efficient packing of apartments to create distinctive spaces.
Somehow, it is a warped vision that sees the inhabitation of a concrete barn built for the storage of the machines of steel that have affected so much of modern American life. Carriage houses have enjoyed the vogue of conversion. So, too, now parking garages.
NOTES

(1) Anderson Park on Cambridge Street in Boston, Massachusetts, is two garages that were recycled into housing in 1978. The developer was Anderson Street Association; the architect was Stull Associates; the structural engineer was Rene Mugnier Associates; the constructor was George B.H. Macomber Company. For British examples see The Architects' Journal, v. 166, no. 27, "Converting Car Parks to Flats."

(2) See US DOT, OST, A Statement of National Transportation Policy, for 1975 and for 1978. Also, NTPSC, National Transportation Policies Through the Year 2000.

(3) This data was furnished by a housing developer operating in the greater metropolitan area of Boston. Projects completed include both new and rehab construction, and were financed both privately and through MHFA.

(4) Klose, Metropolitan Parking Structures, pp. 28-36.

(5) Ibid., p. 31.

(6) Special thanks to Ed Allen for sharing this observation.


(8) Ibid., section 609, pp. 176-78.

(9) Ibid., section 607, pp. 176-76.

(10) Ibid., section 706.0, pp. 201-203.

(11) Ibid., section 718.0, pp. 214-215.

(12) Ibid., section 315.0, pp. 95-99.

(13) Ibid.

(14) Ibid.

(15) Nilson, Design of Prestressed Concrete, p. 316


(18) ACI, Building Code Requirements for Reinforced Concrete, sections 11.4 and 11.5, pp. 42-43.
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