

New Loads for Old Structures

by Shawn Nolan

Is the building strong enough and how can I find out for sure?

Entertainment venues are perhaps among the most varied types of buildings. They can range from new multi-million dollar facilities designed specifically for touring shows to a converted old church to an older legitimate theatre or school facility. While the new performing arts centers get all the attention, it's much more common for a performance venue to be an older or converted facility. The building that once was a warehouse or that began life as a touring house in the '20s now has to be fitted with modern lighting and sound equipment, a rigging system, control booths, etc.

While all of the demands of converting or re-fitting an older building can be daunting, one of the greatest unknowns has to do with the load carrying capacity of the structure. To put it simply: "How can I tell if this old/converted building will hold my new loads?" The loads imposed by large flying units, heavy wagons and modern lighting and sound equipment are not trivial. Every technical director, production manager or facility manager likes to sleep well at night. Getting a good handle on the capacity of your building is a good step in that direction.

DETERMINATION OF CAPACITY — WHERE TO BEGIN

In order to evaluate a new load case and its impact on an existing structure, you need two general sets of information; what are the new and existing load cases and what is the capacity of the structure. I'll treat each of these items separately.

Load Cases

Structural engineers use load cases, as defined by building codes, to determine how to design a structure. A load case is simply the sum of all the loads acting on a structural element or system at one time. Typically, there are several load cases that need to be considered in a complete structural analysis or design. The typical load cases for a roofing system might be:

1. Dead loads
2. Dead and roof live loads
3. Dead and wind loads
4. Dead, roof live and wind loads, etc.

(Note: Roof live loads might include construction loads, rain loads, snow loads or collateral loads such as those imposed by rigging.)

The load case that creates the highest stress in the structural system controls the design. The load case that

usually controls is the one with the largest number of discrete loads. This is, however, not always the case. A roof system design is usually controlled by the combination of dead and roof live loads. In some cases, wind uplift may control parts of the design, especially if the roof framing is light, such as with a bar-joist roof.

For a preliminary evaluation, you will need to know the magnitude of the proposed loads and the combinations of those loads that are likely to occur. It will then be possible to get some feel for the relative magnitude of new and existing loads. This will go a long way towards letting you know if your new load case is small or large relative to the existing loads on the structure.

Current Capacity of the Structure

Structures are generally designed to meet two broad sets of criteria; strength and serviceability. Strength is the ability of the structure to safely support the load without overstressing any part of the structural system. Serviceability addresses the fitness for use of a particular structural component for a specific load case; serviceability is usually defined in terms of deflection (see sidebar). All structural elements deflect to some degree under load and there are limits to allowable (or reasonable) deflection for every structure.

The need to determine the capacity of an existing structural element is directly related to a consideration of risk. What is the risk associated with failure for that structural element; what are the consequences of failure? In order to make an initial guesstimation of the level of risk, it is necessary to define the existing and new load cases. Armed with information about the existing loads and the assumed existing capacity, you can make a judgement regarding how accurate your analysis needs to be.

glossary

Live load: Loads imposed on a structure by people or items that are not permanently attached to the structure.

Dead load: Loads imposed on a structure that are part of the permanent structure.

Load case: A combination of various loads acting simultaneously.

Deflection: A change in the shape of a structural element due to an applied load.

Force: In a classical sense, a force is equal to a mass times an acceleration.

In a more colloquial sense, a force can be thought of as the application of a load (or pressure) to a structural component.

Stress: Force divided by area (e.g. pounds per square foot).

Allowable stress: A stress applied to an element that does not result in a permanent change in the shape of the element.

Failure: A state of overstress that results in a structural element fracturing or deflecting in such a way that it can no longer support the load for which it was designed.

Load path: The series of elements in a structure that resist a specific load.

The magnitude of the new loads relative to the existing loads gives you a good idea of where you stand.

The risk of failure can be viewed from two perspectives: (1) the magnitude of the new loads relative to the existing loads, or (2), the risk of property damage or injury related to failure. Installation of 25 new PAR cans into an existing 4,000 square foot (372 square meter) ceiling will add about 1/8 psf (0.61 kg/m²) to the existing structure. The magnitude of the new load is small, consequently, the risk of failure for the roof system due to the new loads is small. On the other hand, the installation of 25 new line sets, with a rated live load capacity of 1,000 pounds (450 kilos) each will add about 6.25 psf (30.5 kg/m²), not including dead load, to the existing structure. The magnitude is large relative to the existing load cases. In addition, failure of an entire roof system could obviously have large financial and life safety consequences.

DETAILED EVALUATION OF A STRUCTURE — HOW TO PROCEED

There are three methods that are commonly used to evaluate existing structures, which are detailed as follows.

Initial Evaluation

Begin by determining the age of the structure. Buildings built after about 1940 in the U.S. were generally designed to support minimum loads as defined by a building code. If you know or can make an educated guess as to the design loads, this can go a long way in your initial guesstimation about the design capacity of the structure. Prior to 1940, design structural capacity may have been based on a local code, or it may have been based upon the knowledge and skill of the builders. The older the building, the less likely it is that the concept of design loads were used. (See the sidebar for typical building design loads and common load cases in the U.S.) If you cannot find or reasonably assume minimum design loads, you must do some analysis to determine the capacity of the structure.

Let's say that you have been able to determine a reasonable set of minimum design loads. In addition, let's say that the new load case presents a small (less than 1%) increase over existing load cases. With a bit of straightforward arithmetic, you may be able to say that

the new load case is approximately equal to an existing load case and, therefore, the structure is okay.

What do you do if the new load case is large (more than a 2% to 3% increase above the original design loads)? Once again, additional analy-

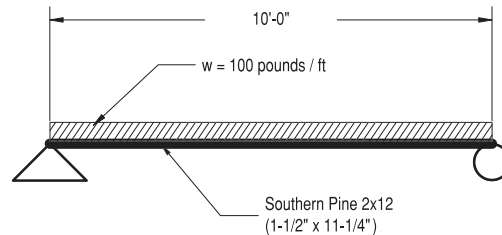
illustration of deflection

Deflection is an important measure of serviceability. For example, a floor system with excessive deflection can feel bouncy or unsafe. Excess deflection can also cause cracks and deterioration of finishes. Under a uniform load, a beam will deflect (bend or sag) according to a standard equation:

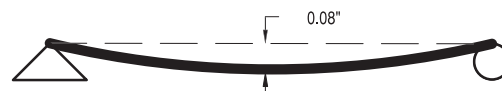
$$\Delta = \frac{5wl^4}{384EI}$$

Delta = deflection (inches)
 5 = a constant
 w = uniform load (pounds per lineal inch)
 l = beam length (inches)
 384 = a constant
 E = modulus of elasticity (pounds per square inch)
 I = moment of inertia (inches⁴)

(Note: Values for E and I for specific materials and standard shapes are readily available from standard references.)



Load Diagram



Deflected Beam

Using the above example, the deflection formula can be solved as follows:

$$\begin{aligned} \Delta &= \frac{5 \left(100 \text{ plf} \times \frac{1 \text{ ft.}}{12 \text{ in.}} \right) \left(10 \text{ ft.} \times \frac{12 \text{ in.}}{1 \text{ ft.}} \right)^4}{384 (1.6 \times 10^6 \text{ psi}) (178 \text{ in.}^4)} \\ &= \frac{5(8.33 \text{ pounds/inch}) (120 \text{ inches})^4}{384 (1,600,000 \text{ psi}) (178 \text{ in.}^4)} \\ &= 0.08 \text{ in.} \end{aligned}$$

Most building codes place a limit on allowable deflection for structural members. One of the more common limiting values applies to live load deflection. The usual U.S. code limitation for deflection of beams in floor systems is beam length divided by 360.

Using this formula, the allowable deflection on the 10-foot beam in the example above is 0.33 in. (10 ft. (12 in. / 1 ft.) / 360). The beam would pass inspection because its actual deflection (0.08 in.) is less than the allowable deflection.

sis is called for and several positive conclusions are possible. You may be able to show that the design loads are less than the actual loads. You may be able to prove that the structure, as built, is stronger than the design load requirements. You may be

able to show that a slightly larger amount of deflection is acceptable. For example, structural engineers frequently use minimum values for design loads. It is unusual in the U.S. to design a modern roof structure for less than 40 psf (195 kg/m²) total

load (20 psf live load, defined by the code, and a 20 psf dead load). Codes typically define live loads, which may not be reduced at the discretion of the designer. Dead loads, on the other hand, simply need to be accounted for. Actual dead loads are frequently less than the design dead loads. A roof structure designed for a 20 psf dead load may actually only be supporting 10 psf, leaving room for some additional load onto the structure.

typical loads and load cases

For the design of building structures, load case combinations are defined by the applicable building code. Load cases are simply a reasonable combination of loads that are likely to act on a structural component at one time. The most common load cases are:

- Dead load
- Dead load + live load
- Dead load + wind or earthquake load
- Dead load + live load + wind or earthquake load

There are many other forces and combinations of forces that may act on a structure, including earth pressure, stress due to changes in temperature, residual stresses from fabrication, etc. When analyzing a structure for gravity (downward acting) forces, dead load + live load will usually control. However, when you are analyzing a large portion of a structure, such as the entire roof, you should be careful to consider the impact of other non-intuitive forces acting on the system. Gravity loads are fairly apparent to most people. Wind loads and other lateral loads on buildings are not so obvious. For example, most roofs act as a diaphragm to transfer lateral wind pressures to a shear wall or a vertical brace. Wind loads on a 30 foot high x 100 foot long (10 meters high x 30 meters long) structure can easily approach 15,000 pounds of force (66.7 kilonewtons) at the end walls. These forces are not trivial and must be accounted for.

sample load case and calculations

Building codes define live loads for various building conditions. Some common live load parameters for floor systems are:

Residential	40 psf
Residential sleeping room	30 psf
Office	50 psf
Public assembly space	100 psf
Theatre stage	150 psf

For most floor systems, the load combination that will control the design and analysis is dead load + live load. Once you have determined the appropriate live load, you can calculate the dead load. For example, the dead load for a wood framed commercial floor assembly might be:

Floor finish (tile, carpet, etc....)	1 psf
Underlayment board	2 psf
Floor sheathing	3 psf
Floor framing	2 psf
Sprinkler system	3 psf
Ducts, lights, misc. mechanical	3 psf
Insulation	1 psf
Gypsum ceiling	2 psf
Total	17 psf

This would be added to the code-determined live load to arrive at the total dead + live load on the flooring system.

Structural Evaluation

If you do not feel comfortable with an approximate analysis, you will have to proceed with greater rigor until you are completely confident in your evaluation of the structure. Begin by locating or developing an accurate set of plans. This will allow you to define complete load paths. Remember, for every action, there is an equal and opposite reaction. The final reaction to any load will be located at the building's foundation. If you have not defined a complete load path for your loads, down to the foundation, you have not adequately modeled the structural system.

The accuracy of your analysis is directly tied to your knowledge of the materials of the existing structure; this knowledge is especially important in older buildings. Not only do you need to know the size of an existing I-beam, you also need to know when it was made to make a reasonable guess as to the material strength. The more information the better. Given a thorough documentation of existing conditions, a very accurate analysis can be performed to assess in place strength of an existing structure. Once you know the capacity of the structure, both in terms of strength and serviceability, it is again straightforward to evaluate the new load case.

In Place Load Tests

Another method for evaluation of existing structure is the use of full-scale load tests. This method can be very valuable in proving that the capacity of an existing structure may significantly exceed the capacity that can be determined by structural analysis.

It might seem to be a paradox that a structure can be proven to be stronger than an analysis would determine. With this in mind, it should be noted that any analysis is a simplification of the real world. Structural analysis is an attempt to create a model (mathematical or otherwise) of the behavior of a building under a certain set of conditions. Many structures have redundancies in their designs that allow them to carry more load than they may have been designed for.

Load tests fall into two general categories, full-scale tests utilizing bulk weights to simulate a specific load or, hydraulic load test set-ups. Full-scale tests using large amounts of bulk material are frequently cumbersome to perform, but they can be very simple and effective. On the other hand, hydraulic load test set-ups are more complicated to execute but they can require far less physical material to execute.

SUMMARY

The structural evaluation of an existing building can be carried out in a wide variety of ways, with a wide range of accuracy. A determination of the relative magnitude of new and existing loads will provide a general

gauge of the risk of imposing a new load onto an existing structure. Once you have a good feel for risk, you can determine if you have adequate information to evaluate the new load case with a reasonable degree of confidence. If you determine you don't have adequate information, keep digging and analyzing until you are comfortable with the answer. If, after an initial assessment you are not fully confident with your analysis, you may want to contact a structural engineer. How can you tell if you need some assistance? The need for outside assistance can be related to the project's risk. If the risk is high and you don't feel comfortable with your results, some outside help may be justified.

The method outlined above can be applied by just about anyone willing to be diligent and do some basic math. In some cases, you can do your own evaluation and feel quite comfortable that the structure is safe. This being said, don't take a chance with life safety—keep evaluating until you are sure that you have a comfortable and conservative answer. Remember, the old tech director's motto that "I like to be able to sleep at night" is just a colloquial way of saying "I trust my information, I trust

my analysis, the structure is safe."

Disclaimer and References

This article is not intended to be a thorough treatment of the topic of structural evaluation of existing buildings. Local, state and national building codes may need to be consulted prior to the renovation of existing structures. The author cannot be responsible for any evaluation based solely upon this article.

Readers interested in more information may find the following basic structural analysis texts to be of interest: *Simplified Engineering for Architects and Builders*, 9th Edition by James E. Ambrose and *Structural Design for the Stage* by Alys E. Holden and Bronislaw J. Sammler. ●

Shawn Nolan has worked in regional theatre, trade shows and TV scenery for more than 20 years. He completed his BS in Civil Engineering at the University of Cincinnati in 1997 and has been working as a structural engineer for the past five years. He heads up Entertainment Structures Group (a division of Steven Schaefer Associates, Inc.), a specialty engineering firm providing consulting services to the trade. His areas of expertise include stage machinery, structural design of steel and wood structures and forensic evaluation of existing structures. He can be reached at: shawn.nolan@entertainmentstructures.com.