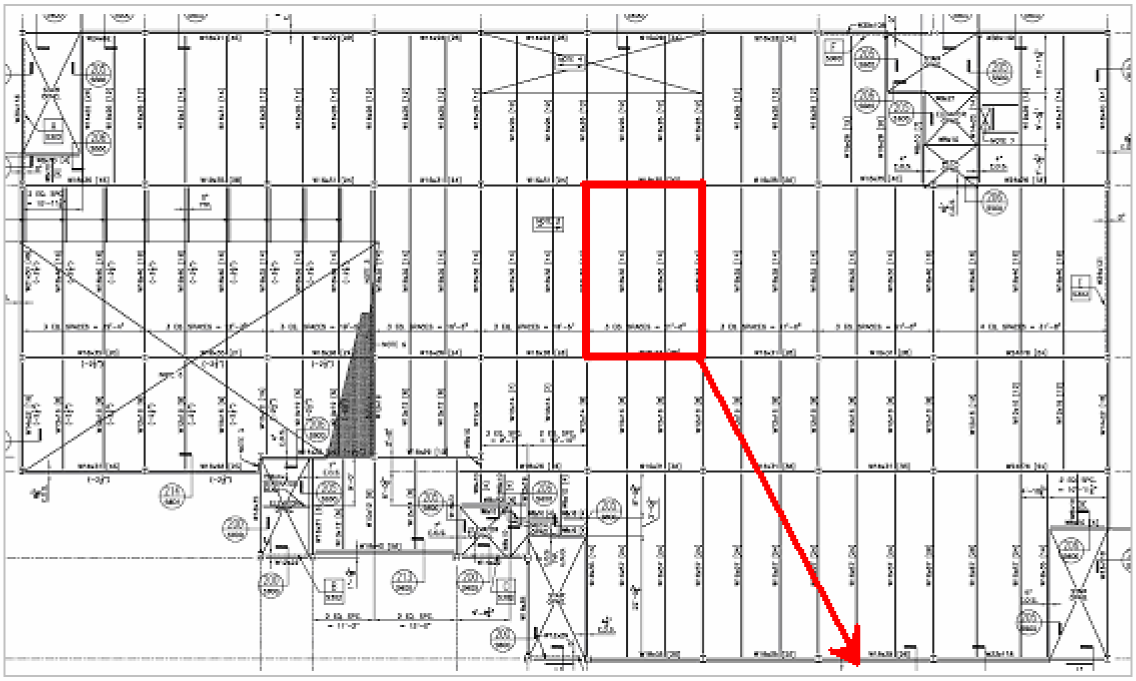
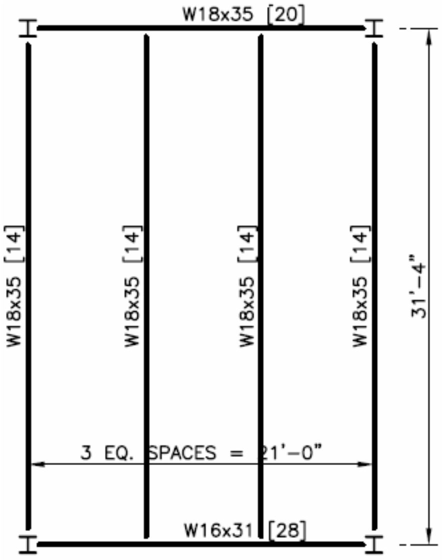
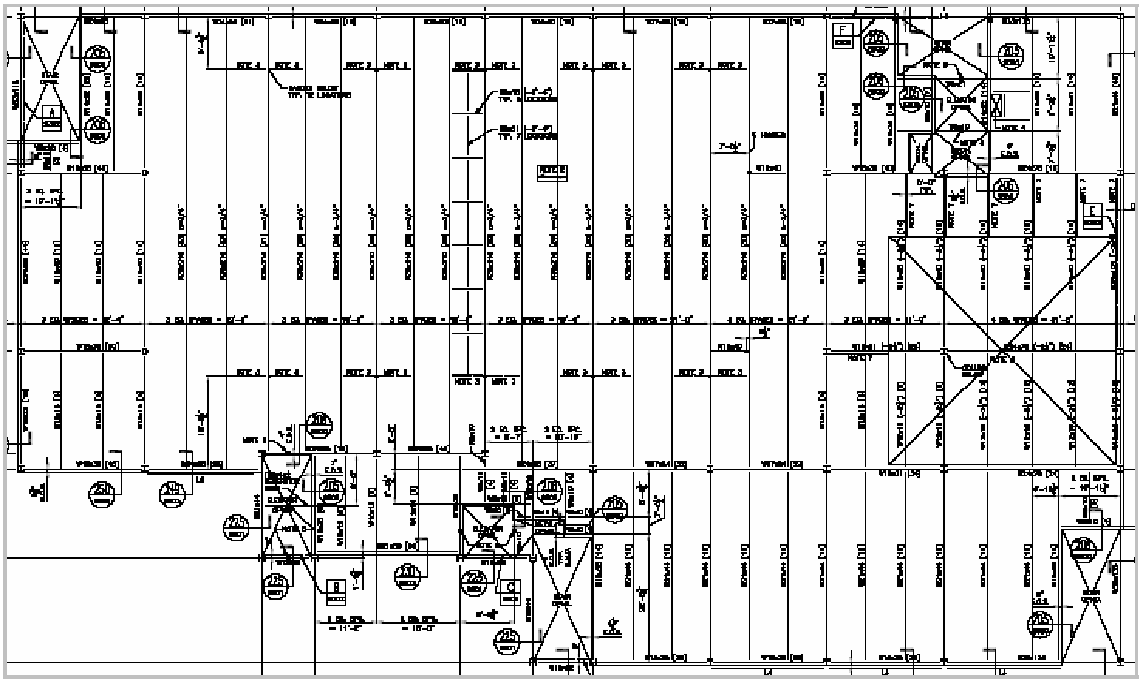
Existing Gravity System

Duquesne University's Multipurpose Athletic Facility is supported by a steel superstructure, including a composite steel floor system. Each of the first three floors is framed in rectangular bays, ranging in size from 20'x20' to 21'x34'. The lower floors are used to house a multitude of mixed facilities including a bookstore and coffees shop, offices, classrooms, aerobic/dance rooms, and athletic spaces.



**** Typical Framing Plan----floors Forbes-3rd ****





****Gymnasium and Ballroom Framing Plans ****

Of the two athletic/gymnasium spaces, one is framed similarly to that of a typical floor, while the other is designed under different circumstances. The second gymnasium is located on the 4th floor, directly above gymnasium one. The 5th floor is used to house a ballroom or entertainment space. Since these spaces must be completely devoid of columns, the framing consists of W36x210's with ¾" camber, spanning 80'. These beams frame into smaller span girders, typically W27x84 members.

Analyzed Spaces

As stated in the introductory portion of my structural depth section, I will focus my analysis on floor vibration. This analysis seems to be an especially relevant issue due to the close proximity of active and inactive spaces at the lower levels as well as the ballroom space that will be used for both dancing and dining purposes. Within the new Duquesne University Multipurpose Facility, vibrations caused by rhythmic activity are the most prevalent. In an attempt to look at the most critical areas, I will study 4 separate areas in which rhythmic excitation will be the most severe, including:

- 2nd floor aerobics studio
- 3rd floor gymnasium (typical bays)
- 4th floor gymnasium (long spans)
- 5th floor ballroom (long spans)

Vibration Design Criteria

For my analysis, I will consult AISC's Design Guide 11 (DG 11), Floor Vibrations Due to Human Activity. As stated in the design guide, "the primary objective is to provide basic principles and simple analytical tools to evaluate steel framed floor systems for vibration serviceability due to human activity."

Floor Vibrations in General

When designing a floor structure, strength and general serviceability requirements (deflection, etc…) are always taken into consideration. Other serviceability issues, such as vibration requirements, are not always given proper consideration, especially if it is not requested by an owner, or demanded by the use of sensitive equipment. Often times, vibration checks are not completed until some sort of issue with the structures performance is reported.

A person's perception of "annoying floor vibrations" is strongly related to their environment and state of activity. For example, a person working in an office or classroom will not tolerate mildly perceptible vibrations, while a person undertaking physical activity will generally tolerate "vibrations 10 times greater." An inactive person located near an area of rhythmic activity will generally tolerate some level in between.

Rhythmic Excitation

Rhythmic excitation of floor systems is addressed in Chapter 5 of DG 11. The criterion for design is based on activity occurring over either a partial or entire floor area. It is used to evaluate "structural systems supporting aerobics, dancing, or audience participation events." The method of evaluation is based on two significant system characteristics: floor frequency and acceleration. The following equations (from DG 11) were used to determine the natural frequency of the floor system and its peak acceleration, respectively.

$$f_n = 0.18\sqrt{g/(\Delta_j + \Delta_g + \Delta_c)}$$

$$f_n \geq (f_n)_{req'd} = f\sqrt{1 + \frac{k}{a_o/g}\frac{\alpha_i w_p}{w_t}}$$

$$\frac{a_p}{g} = \frac{1.3\alpha_i w_p / w_t}{\sqrt{\left[\left(\frac{f_n}{f}\right)^2 - 1\right]^2 + \left[\frac{2\beta f_n}{f}\right]^2}}$$

For rhythmic design, the following tables offer acceptable values for use in conjunction with the previous design equations.

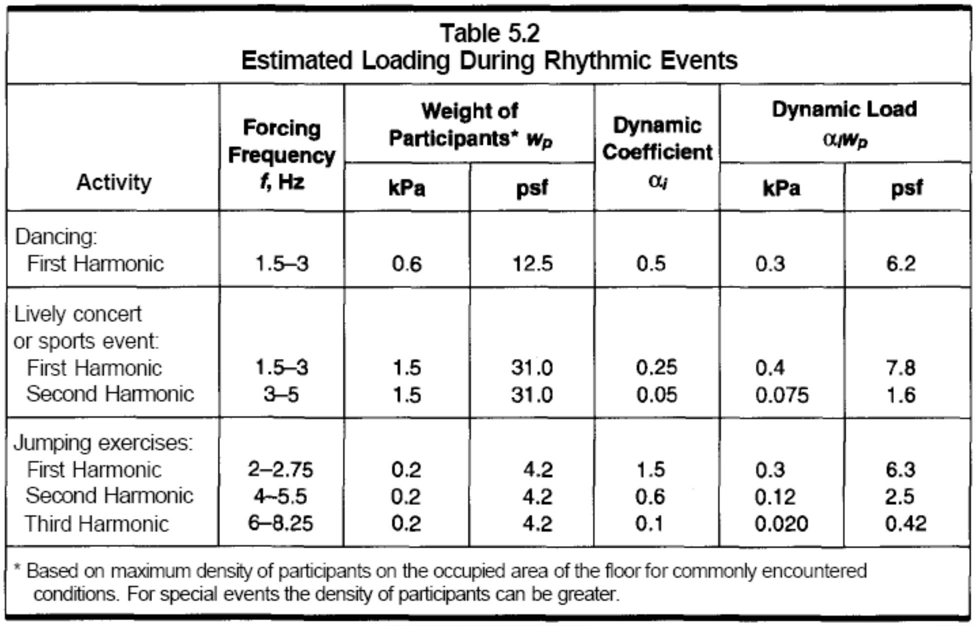


Table 5.2
Estimated Loading During Rhythmic Events

Activity	Forcing Frequency f, Hz	Weight of Participants* w_p		Dynamic Coefficient α_i	Dynamic Load $\alpha_i w_p$	
		kPa	psf		kPa	psf
Dancing:						
First Harmonic	1.5–3	0.6	12.5	0.5	0.3	6.2
Lively concert or sports event:						
First Harmonic	1.5–3	1.5	31.0	0.25	0.4	7.8
Second Harmonic	3–5	1.5	31.0	0.05	0.075	1.6
Jumping exercises:						
First Harmonic	2–2.75	0.2	4.2	1.5	0.3	6.3
Second Harmonic	4–5.5	0.2	4.2	0.6	0.12	2.5
Third Harmonic	6–8.25	0.2	4.2	0.1	0.020	0.42

* Based on maximum density of participants on the occupied area of the floor for commonly encountered conditions. For special events the density of participants can be greater.

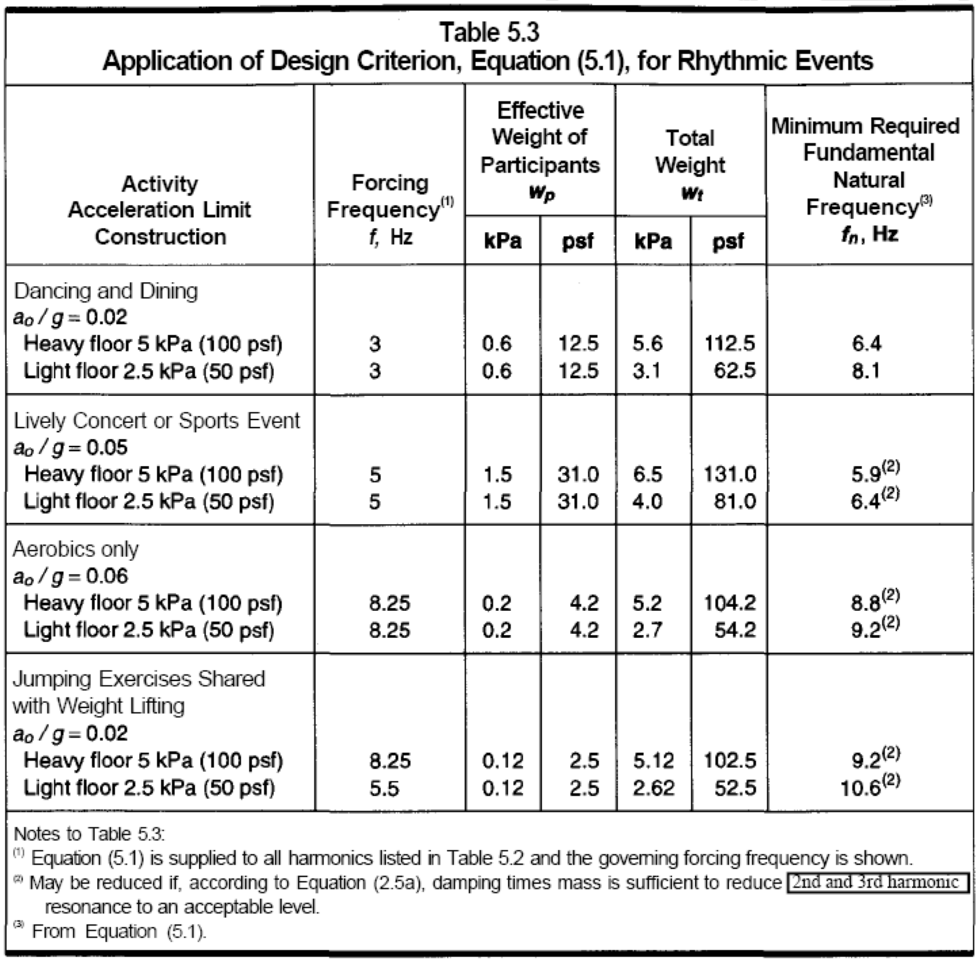


Table 5.3
Application of Design Criterion, Equation (5.1), for Rhythmic Events

Activity Acceleration Limit Construction	Forcing Frequency$^{(1)}$ f, Hz	Effective Weight of Participants w_p		Total Weight w_t		Minimum Required Fundamental Natural Frequency$^{(3)}$ f_n, Hz
		kPa	psf	kPa	psf	
Dancing and Dining						
$a_o / g = 0.02$						
Heavy floor 5 kPa (100 psf)	3	0.6	12.5	5.6	112.5	6.4
Light floor 2.5 kPa (50 psf)	3	0.6	12.5	3.1	62.5	8.1
Lively Concert or Sports Event						
$a_o / g = 0.05$						
Heavy floor 5 kPa (100 psf)	5	1.5	31.0	6.5	131.0	5.9$^{(2)}$
Light floor 2.5 kPa (50 psf)	5	1.5	31.0	4.0	81.0	6.4$^{(2)}$
Aerobics only						
$a_o / g = 0.06$						
Heavy floor 5 kPa (100 psf)	8.25	0.2	4.2	5.2	104.2	8.8$^{(2)}$
Light floor 2.5 kPa (50 psf)	8.25	0.2	4.2	2.7	54.2	9.2$^{(2)}$
Jumping Exercises Shared with Weight Lifting						
$a_o / g = 0.02$						
Heavy floor 5 kPa (100 psf)	8.25	0.12	2.5	5.12	102.5	9.2$^{(2)}$
Light floor 2.5 kPa (50 psf)	5.5	0.12	2.5	2.62	52.5	10.6$^{(2)}$

Notes to Table 5.3:

(1) Equation (5.1) is supplied to all harmonics listed in Table 5.2 and the governing forcing frequency is shown.

(2) May be reduced if, according to Equation (2.5a), damping times mass is sufficient to reduce 2nd and 3rd harmonic resonance to an acceptable level.

(3) From Equation (5.1).

Gravity System Evaluation

Before performing any type of analysis, there seemed to be two alternate types of framing members that would satisfy both vibration and economic concerns; open web steel joists and castellated beams. Both types of framing were considered based on presumed weight savings and the ability to span long distances.

During my evaluation, it I found it difficult to meet specific vibration criteria in both the typical and long span situations using steel joists. Depth of the floor system became an issue when the joist sizes needed to increase by 12-18" in order to meet a total load deflection requirement of L/360. Also, the use of joist would require a closer spacing, resulting in at least 2-3 times more joists than existing wide flange framing.

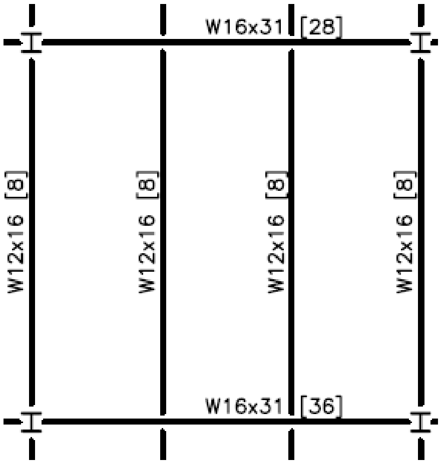
2^{nd} *Floor Aerobic/Fitness Studios*

Existing Framing: (20'8" span)

Beams: **Composite W12x16 @ 7'o.c.**
Girders: **Composite W16x31 (21'0")**
Slab: **(NWC) 4.5" slab, 2" deck**
Other: **10 psf wood overlay**
DL + w_p: **89 psf**

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1^{st} Harmonic	2^{nd} Harmonic	a_p/g (%g)	a_o/g (%g)
8.48	5.38	8.03	0.045	0.06

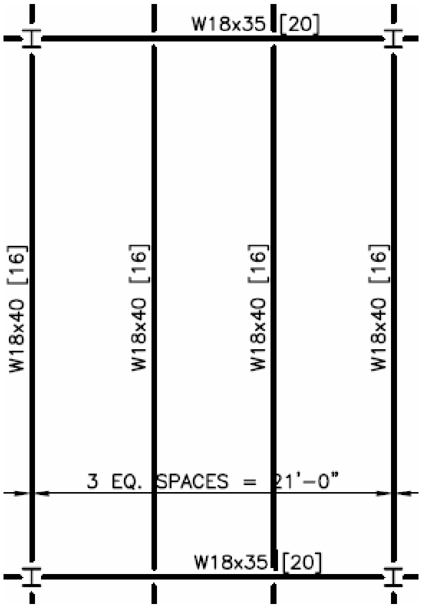
Based on the information calculated above, this particular floor area is acceptable for vibration based on aerobic only use. The natural frequency of the floor system exceeds both the first and second harmonics and the acceleration limit is satisfactory. Since the natural frequency of the floor is closest to the forcing frequency for the 3^{rd} harmonic, the peak acceleration was checked for that particular case.



Existing Framing: (31’4” span)

Beams: **Composite W18x40 @ 7’o.c.**
Girders: **Composite W18x35 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**
Other: **10 psf wood overlay**
DL + w_p: **89 psf**

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
5.18	5.38	8.03	0.45	0.07



Even with a larger beam for the longer span, the natural frequency of the floor system does not meet the required 1st or 2nd harmonic frequencies for aerobic loading conditions.

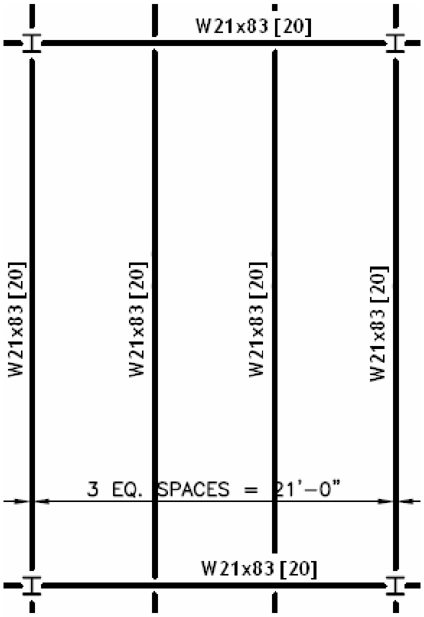
With a retail space below, the vibration concerns in this aerobic space should be properly rectified. First, I attempted to use a W18 member to reach the required criteria. Once the beam weight became double the original, I decided to switch to a deeper member. In trying to minimize any kind of depth increase, the largest beam chosen was a W21. After much trial and error, the beam settled on to meet the vibration requirement was a W21x83.

New Framing: (31’4” span)

Beams: **Composite W21x83 @ 7’o.c.**
Girders: **Composite W21x83 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**
Other: **10 psf wood overlay**
DL + w_p: **89 psf**

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
8.07	5.38	8.03	0.051	0.06

With the increase in beam and girder size, deflections (which are inversely proportional to floor frequency) decreased, and the first two harmonic frequencies were met. Furthermore, the peak acceleration was also limited, making the floor acceptable for the aerobic vibration criteria. If W21 beams were deemed to be too large, one could use lower forcing frequencies to lessen the required frequencies, and obtain acceptable results.



3rd Floor Gymnasium (typical bays)

Existing Framing: (31’4”span)

Beams: **Composite W18x35 @ 7’o.c.**
Girders: **Composite W16x31 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**
DL + w_p: **89 psf**

At this gymnasium level, the floor is framed in the typical style used in the lower levels of the Duquesne University facility. It is framed with similar members and at the same span and spacing of the second aerobic bay. When analyzing the joist mode only, the framing is more than satisfactory, performing at a peak acceleration of around 5%**g**.

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
8.43	4.97	7.6	0.047	0.07

When analyzing the combined joist and girder modules, the results are as follows:

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
5.78	4.97	7.6	0.111	0.07

While the peak acceleration limit is exceeded, the gym is not a total failure. Assuming the participants using the gymnasium would not be disturbed by their own induced vibrations, the acceleration limits could be increased slightly to around 10-15%**g**. Unfortunately the gym is not isolated. Office space below and an adjacent weight lifting facility dictate that the vibrations caused by the gymnasium should be held to a reasonable criterion of 5%**g**. To meet more strict criteria, I would recommend changing the framing to W 21x83 beams and girders as was done for the aerobic spaces. In addition, increasing the slab depth to 7.5” would bring the required harmonic frequencies under the existing natural floor frequency.

4th Floor Gymnasium (long spans)

Existing Framing: (79’6” span)

Beams: **Composite W36x210 @ 7’o.c.**
Girders: **Composite W27x84 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**
DL + w_p: **89 psf**

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
3.89	4.27	6.8	0.089	0.10

The second gymnasium space is quite different than the first. This is the first level that is framed in a long spanning condition. Also, this floor is one that is used solely for athletic purpose, relaxing the condition of designing for sensitive areas on that particular floor. With that said, I will use a peak acceleration criterion for the gym of 10%**g**.

The existing floor system does not meet the frequency requirements, but its peak acceleration is below the new limit. While the floor seems to be marginally acceptable, possible improvements could be made by using an alternative system. First, non-composite open web steel joists were considered, but were not able to practically meet vibration requirements over such a great span. One system that met strength, weight and vibration requirements was castellated beams. A castellated beam is a wide flange section that is cut along its web in a flat saw tooth pattern, shifted, and welded back together to create a deeper beam. The new beam contains hexagonal web openings, and is stiffer than the original. The resulting member is one that is lighter and can be used to span greater lengths.

Castellated beams used in the adjacent Duquesne University Parking Garage

Castellated Beam Framing:

Beams: **Composite CB50x169 @ 7'o.c.**
Girders: **Composite W27x84 (21'0")**
Slab: **(NWC) 4.5" slab, 3" deck**
DL + w_p: **89 psf**

	$f_{n(reqd)}$ (Hz)			
$f_{n(act)}$	1st Harmonic	2nd Harmonic	a_p/g (%g)	a_o/g (%g)
4.6	4.27	6.8	0.051	0.10

The use of castellated beams provides a lighter overall floor system, meeting the 1st harmonic frequency requirement and reducing the peak acceleration of the floor. Even when computed using the 2nd harmonic forcing frequency (5.5 Hz) the peak acceleration is close to the prescribed 0.10 limit.

a_p/g (%g)	a_o/g (%g)
0.116	0.10

5th Floor Ballroom (long spans)

Existing Framing: (79’6” span)

Beams: **Composite W36x210 @ 7’o.c.**
Girders: **Composite W27x84 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**
DL + w_p: **89 psf**

$f_{n(act)}$	$f_{n(reqd)}$	a_p/g (%g)	a_o/g (%g)
3.89	5.4	0.105	0.02

In my first attempt to analyze this ballroom space, I have considered more than half of the floor area to be used for dancing. This may be a somewhat unrealistic assumption, but it will be used to asses the current state of the framing. The results above indicate that the floor is not only designed below the required natural frequency but also has an extremely high peak acceleration value when compared to the allowable maximum for ballroom spaces. This information suggests that occupants dining on the same floor will experience a high level discomfort due to excessive vibrations.

For my second evaluation, I made the decision to consider only a portion of the floor area be used for dancing. This assumption was made after reviewing an AISC engineering journal paper written by Dr. Linda Hanagan entitled “Dynamic Amplitude Prediction for Ballroom Floors”. The paper discusses “a modification in the design of long span ballroom floors, where dancing activities are likely to take place in only a limited area of the bay”. This approach is used to modify the constant “k”, and in turn reduce the calculated peak acceleration of the floor system. The equations used to determine the modified k factor are shown below.

$$k = \frac{2\pi}{\ell_g \ell_j}\left(\sqrt{c_j} + \sqrt{c_g}\right)\left[\ell_j\sqrt{c_j}\left(\ell_{g2} - \ell_{g1}\right)\left(\cos\frac{\pi\ell_{j1}}{\ell_j} - \cos\frac{\pi\ell_{j2}}{\ell_j}\right) + \ell_g\sqrt{c_g}\left(\ell_{j2} - \ell_{j1}\right)\left(\cos\frac{\pi\ell_{g1}}{\ell_g} - \cos\frac{\pi\ell_{g2}}{\ell_g}\right)\right]$$

*Ch. 2 of DG11 defines “k” to be 1.3 for dancing

$$c_j = \frac{\Delta_j^2}{\pi^2\Delta_j^2 + 16\Delta_j\Delta_g + \pi^2\Delta_g^2}$$

$$c_g = \frac{\Delta_g^2}{\pi^2\Delta_j^2 + 16\Delta_j\Delta_g + \pi^2\Delta_g^2}$$

In my first attempt to use this new criterion, I chose to load half the span of each bay. In doing so, the modified constant k=0.92. The new framing and resulting values are as follows:

Beams: **Composite W40x372 @ 7’o.c.**
Girders: **Composite W30x90 (21’0”)**
Slab: **(NWC) 4.5” slab, 2” deck**

$f_{n(act)}$	$f_{n(reqd)}$	a_p/g (%g)	a_o/g (%g)
5	5.4	0.03	0.02

Using the modified factor improved both the frequency and peak acceleration numbers greatly, but not to an acceptable level. After careful consideration, I chose to reduce the area used for dancing to ¼ of the 80' span. Once again the k factor was reduced (k=0.46), and the peak acceleration reached an acceptable level.

a_p/g (%g)	a_o/g (%g)
0.019	0.02

This increased design is sufficient for vibration criteria, but is extremely heavy compared to the existing framing. Once again, castellated beams were chosen as a lighter alternative to the existing wide flange shapes.

Castellated Beam Framing:

Beams:	**Composite CB50x221 @ 7'o.c.**
Girders:	**Composite W27x84 (21'0")**
Slab:	**(NWC) 4.5" slab, 2" deck**
DL + w_p:	**89 psf**

$f_{n(act)}$	$f_{n(reqd)}$	a_p/g (%g)	a_o/g (%g)
5.4	5.4	0.019	0.02

The castellated beam system meets vibration requirements and is approximately the same weight as the existing floor system. For those two reasons, the castellated members are the most efficient choice to be used for this design.

Gravity Analysis Results

	Framing Weight (kips)	
Floor Use (Floor #)	Existing	Alternate
Ballroom (5th)	428.9	406.2
Gym (4th)	377.5	321.9
Gym (3rd)	127.4	162.8
Aerobic (2nd)	132.2	153.8
Totals	1066	1044.7

Using the vibration criteria for steel framed floor systems outlined in AISC Design Guide 11, I was able to design each floor system in a satisfactory manner. During the process of analyzing the typically framed aerobic and gym areas, it became evident that the most practical solution to vibration related issues was to increase beam depth. Even when considering spatial requirements for floor to ceiling height, the 3" depth increase is not enough to cause concern.

In dealing with the long spans, castellated beams were determined to be the most effective floor system based on weight and serviceability. The use of these members at the 4th floor gym level reduced the beam weight from 210 PLF to 169 PLF. The ballroom area was designed in a slightly different manner due to the more strict vibration criteria. This criterion did not allow the weight of this area of the floor system to be reduced; however, the use of castellated beams kept the weight approximately the same as the existing system. The ability to use castellated beams in another long spanning area lessened the overall weight of the entire floor.

Although the use a castellated beam system was a benefit in terms of weight savings, the depth of each beam was increased by 14". The clear height for each gymnasium was cut from 23'0" to 21'8". Each gym's primary use is for basketball, a sport that requires a certain amount of unobstructed overhead space. While a 21'8" ceiling would be unusable for competitive high school or college athletics, it is perfectly acceptable for recreational play.