APPLICATION NOTE AN011

Low-Bay Lighting

2009.09.22

1. Overview

Future Lighting Solutions has developed an LED-based low-bay lighting system leveraging LUXEON® Rebel LEDs, providing a complete solution to enable applications in key market segments, such as parking garage lights.

The design comprises of an enclosed fixture, shown in Figure 1, which includes the optical, thermal, and power solutions, as well as a light engine demonstrating different LED configurations that utilize different power solutions.

All the solutions described in this application note are available at Future Lighting Solutions to enable the implementation of the system for prototyping or volume production.

Demo kits that include the lighting units have been assembled to showcase the functionality of the design and prove its ability to serve the market needs. These kits are available to be presented to demonstrate the design.

Figure 1. Low-bay enclosed fixture

ENERGY STAR for Solid-State Lighting has not finalized requirements for low-bay lighting performance. Therefore, conducting research in the general lighting market revealed certain parameters that the lighting industry requires for such application. These parameters were used as a starting point in developing an LED-based low-bay lighting system. Table 1 lists the gathered requirements.

Note: This application note will be updated once the ENERGY STAR requirements for low-bay lighting are finalized.

Target Luminaire Light Output	Min. 50 lux, Avg. 75 lux
Target Area Covered by Light	2.5 m mounting height; very wide viewing angle
Target Luminaire Efficacy	60 lm/W
Target Luminaire Lifetime	50,000 hours
Target Luminaire CCT	Neutral White (4000K)
Input Voltage Range	Universal AC or dedicated AC (120V or 230V)
Power Factor Requirement	0.9

Table 1. Performance requirements for low-bay lights

2. SSL Designer Analysis

The SSL Designer software (www.futurelightingsolutions.com/ssldesigner) takes the target light specifications such as the efficacy, illuminance, system lifetime, along with the maximum LED drive current as input parameters. It then determines the required minimum number of LEDs to meet or surpass the provided specifications. Moreover, it calculates the usable light (lm), the usable efficacy (lm/W), and the total power consumed by the LED-based system (W), amongst other output parameters.

In order to meet the specifications for the low-bay lighting application, the following is the SSL designer analysis results:

- **Input Parameters:**
  After selecting the target market and application, a uniform illuminance of 75 lux is set to illuminate a square surface of 7.5m by 7.5m. The input section with the set parameters is shown in Figure 2.
- **LED System vs. Conventional Lamp System Performance Comparison:**
  After entering the application input parameters and entering basic information about the light source, SSL Designer calculates the required LED system performance, including the LED count and drive current. In addition, the tool calculates the performance of a conventional lamp system that meets the same specifications. Figures 3 and 4 show the performance calculations of both cases respectively. The results state that 48 LEDs driven at 350mA current are required to meet the specifications of light output, efficacy, and lifetime, while maintaining the junction temperature at an acceptable value for suitable LED operation. The total power consumption of the LED system was 57.77W, after losses, while that of the conventional lamp system was 187.5W. This shows the significant improvement achieved, in terms of power consumption, when using LEDs in low-bay applications.

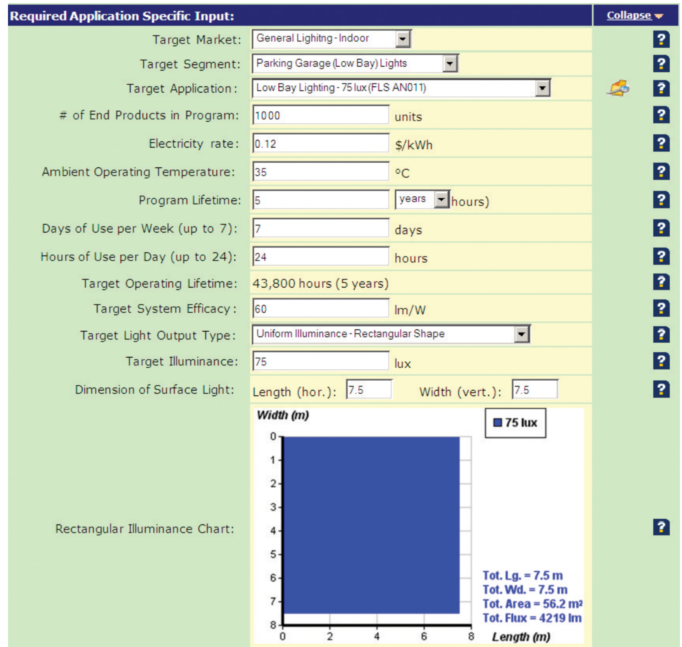
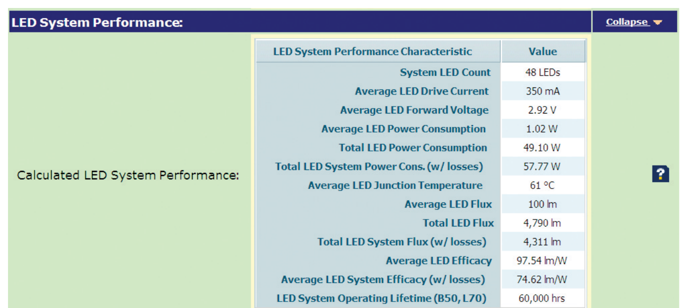


Figure 2. SSL Designer Input

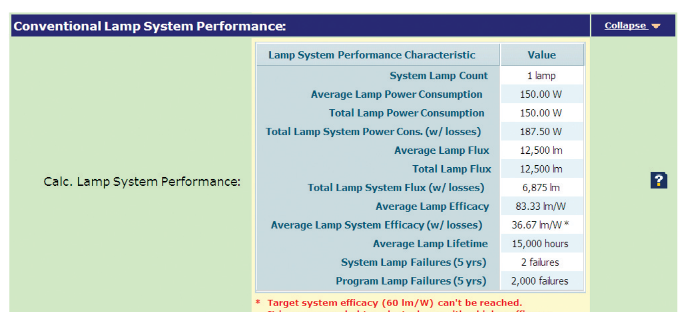


LED System Performance:

Calculated LED System Performance:

LED System Performance Characteristic	Value
System LED Count	48 LEDs
Average LED Drive Current	350 mA
Average LED Forward Voltage	2.92 V
Average LED Power Consumption	1.02 W
Total LED Power Consumption	49.10 W
Total LED System Power Cons. (w/ losses)	57.77 W
Average LED Junction Temperature	61 °C
Average LED Flux	100 lm
Total LED Flux	4,790 lm
Total LED System Flux (w/ losses)	4,311 lm
Average LED Efficacy	97.54 lm/W
Average LED System Efficacy (w/ losses)	74.62 lm/W
LED System Operating Lifetime (B50, L70)	60,000 hrs

Figure 3. LED System Performance



Conventional Lamp System Performance:

Calc. Lamp System Performance:

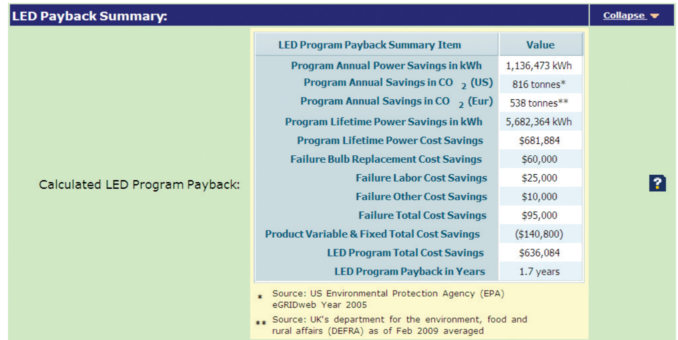
Lamp System Performance Characteristic	Value
System Lamp Count	1 lamp
Average Lamp Power Consumption	150.00 W
Total Lamp Power Consumption	150.00 W
Total Lamp System Power Cons. (w/ losses)	187.50 W
Average Lamp Flux	12,500 lm
Total Lamp Flux	12,500 lm
Total Lamp System Flux (w/ losses)	6,875 lm
Average Lamp Efficacy	83.33 lm/W
Average Lamp System Efficacy (w/ losses)	36.67 lm/W *
Average Lamp Lifetime	15,000 hours
System Lamp Failures (5 yrs)	2 failures
Program Lamp Failures (5 yrs)	2,000 failures

* Target system efficacy (60 lm/W) can't be reached. It is recommended to select a lamp with a higher efficacy.

Figure 4. Conventional Lamp System Performance

- **LED Payback:**
  One more feature in the tool is to calculate the payback of using an LED system as compared to using a conventional lamp system. After defining cost information for both systems, the tool produces payback information such power savings, cost savings, and payback period. Figure 5 shows that the payback period for using an LED-based system for low-bay lighting is 1.7 years.

Note: The above SSL Designer case is available as a default scenario that can be loaded in the tool and used as reference. Under "Target Application" select "Low Bay Lighting – 75 lux (FLS AN011)" to load all the case parameters.



LED Payback Summary: Collapse

Calculated LED Program Payback:

LED Program Payback Summary Item	Value
Program Annual Power Savings in kWh	1,136,473 kWh
Program Annual Savings in CO_2 (US)	816 tonnes*
Program Annual Savings in CO_2 (Eur)	538 tonnes**
Program Lifetime Power Savings in kWh	5,682,364 kWh
Program Lifetime Power Cost Savings	$681,884
Failure Bulb Replacement Cost Savings	$60,000
Failure Labor Cost Savings	$25,000
Failure Other Cost Savings	$10,000
Failure Total Cost Savings	$95,000
Product Variable & Fixed Total Cost Savings	($140,800)
LED Program Total Cost Savings	$636,084
LED Program Payback in Years	1.7 years

* Source: US Environmental Protection Agency (EPA) eGRIDweb Year 2005

** Source: UK's department for the environment, food and rural affairs (DEFRA) as of Feb 2009 averaged

Figure 5. LED Payback

3. LUXEON LEDs

48 Neutral White LUXEON Rebel LEDs were used in the low-bay light design (p/n. LXML-PWN1-0100).

A significant increase in performance will be achieved when the new LUXEON Rebel Illumination Portfolio LEDs are incorporated in the design. This is due to the improvements in the hot/cold factor, which generates increased light output at higher junction temperatures.

For instance, the LUXEON Rebel LXML-PW51, from the Illumination Portfolio, is rated to provide a nominal CCT of 4000K, thus meeting the target CCT as indicated in Table 1 above. Table 2 illustrates the advantages from a Usable Light Tool analysis (www.futurelightingsolutions.com/ult) of the improved hot/cold factor of the LXML-PW51:

48 LEDs	LXML-PWN1-0100	LXML-PW51
Current (mA)	375	375 / 500
Junction Temperature (°C)	99	98 / 107
Light Output (lumens)	4414	4603 / 5588

Table 2. Comparison between different LUXEON Rebel LEDs

3.1. Board Design and LED Connections

The board used to mount the LEDs is an FR4 board with thermal vias of dimensions of 240mm x 240mm, with 62mils of FR4 and 2oz. Copper.

The board was designed to support a high degree of flexibility, hence providing the ability to adapt to different possible power solutions. The 48 LEDs are divided in clusters of 6 LEDs in series. Each 6 LED cluster can be dynamically connected in series or parallel to another 6 LED cluster depending on a connector configuration. For instance, the same board can be configured by means of different jumper settings to have 1 string of all 48 in series, 4 parallel strings of 12 LEDs in series, or 8 parallel strings of 6 LEDs in series, to accommodate different driver options.

Furthermore, 2 LEDs every second 6 LED cluster can be powered by a 12V battery for emergency lighting to guarantee a minimum illuminance (lux) for a certain period of time. As a result, in situations when a power outage takes place, a few LEDs remain lit to maintain the light output at a sufficient illuminance value on for that period of time.

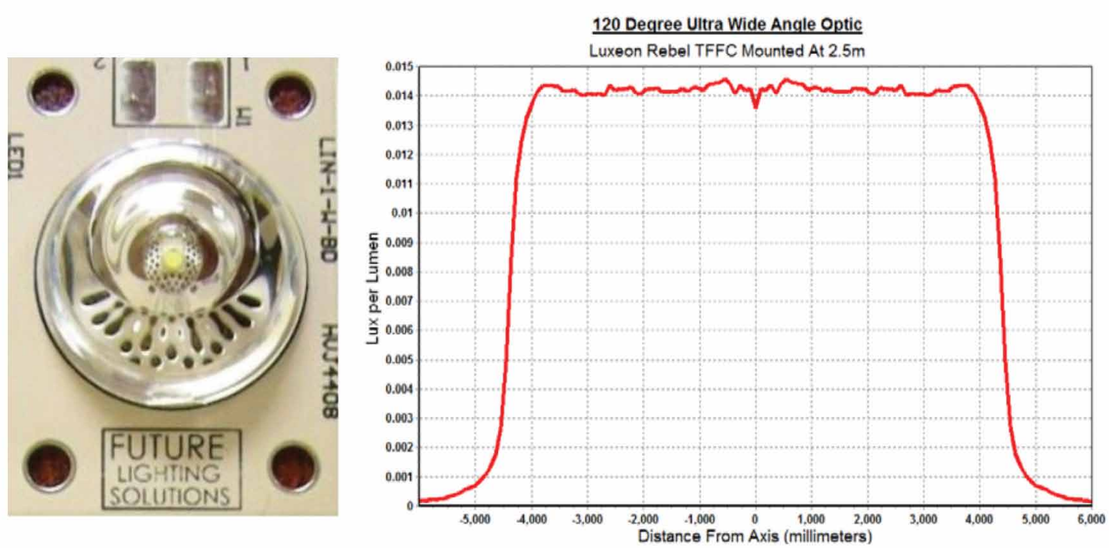
Figure 6 below shows the LEDs mounted on the FR4 board with the optics placed on each LED. ON and OFF states are illustrated in the figure.

Figure 6. LED board with optics

4. Optical Solutions

Although the LUXEON Rebel LED has a wide viewing angle of 140 degrees, the radiation pattern is lambertian, which does not generate a uniform luminance on the illuminated surface. Furthermore, using the LEDs without optics may create hot spots on the target surface.

The Carclo Bubble Optic (p/n. 10403), shown in Figure 7(a), was used to provide uniform illumination. Figure 7(b) illustrates the uniformity of the illumination over the target surface. The optic has a viewing angle of 120° and its optical efficiency is greater than 90%, which maximizes the light output utilization and minimizes the LED count.



(a) (b)

Figure 7. (a) LED with Carclo Bubble Optic, (b) Radiation pattern of Bubble optic

4.1. Optical Simulations and Measurements

An optical simulation was performed to evaluate the performance of the fixture. The simulation model produced 5000 lumen/lamp with 120 degree optic.

Figure 8 below shows the illuminance on the surface of four overlapping fixtures. The spacing between fixtures is 20 ft Horizontal and 20 ft Vertical. According to the illuminance scale below, the average illuminance level of 70 lux required by the target specification is clearly met in the illustration of the four simulated fixtures.

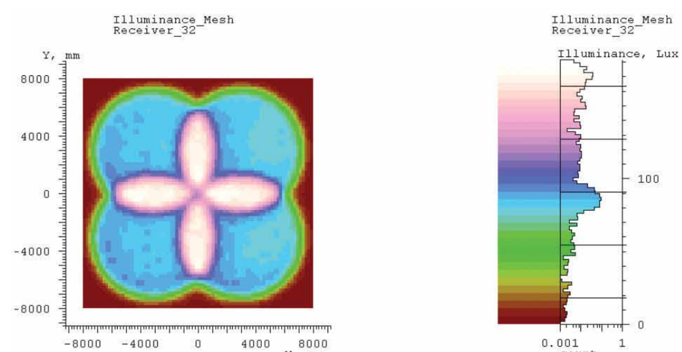


Figure 8. Optical simulation results of 4 overlapping low-bay units

5. Thermal Solutions

A 247.65mm (9.75") long black anodized finished extrusion heat sink from Aavid Thermalloy with 0.40°C/W thermal resistance, was used to mount the LED board (p/n. 627253B09750G). The heat sink and its dimensions are shown in Figure 9.

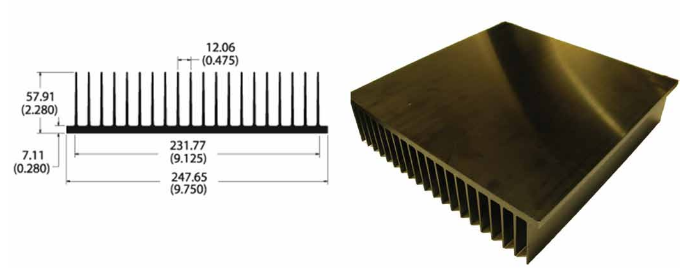


Figure 9. Aavid Thermalloy heat sink used for the low-bay light unit

5.1. Thermal Simulations and Measurements

A thermal simulation was performed to evaluate the overall thermal performance of the fixture. QLED Thermal Simulation software (www.futurelightingsolutions.com/qled) was used to model the fixture and perform the simulation, as shown in Figure 10.

The QLED model was run with a forward current of 350mA, and ambient temperature of 22°C. The resulting junction temperature of the simulation was 83.16°C, well below the maximum junction temperature of 150°C.

In addition to the thermal simulation, measurements using a thermocouple were taken on a fully operational assembly to monitor its thermal behavior. The thermocouple was placed at the solderability measurement point (Ts) as per the LUXEON Rebel Thermal Measurement Guidelines (AB33), shown in Figure 11.

The calculations below demonstrate how to obtain the junction temperature of the LED, taking into account the drive current, the LED forward voltage, and the thermal resistance from junction to the solderability measurement point:

Ts = 66.6°C (thermocouple measurement)
$T_j = T_s + P*R\theta(J-S)$
$T_j = 62.5 + (0.35*2.9)*16 = 82.8°C$

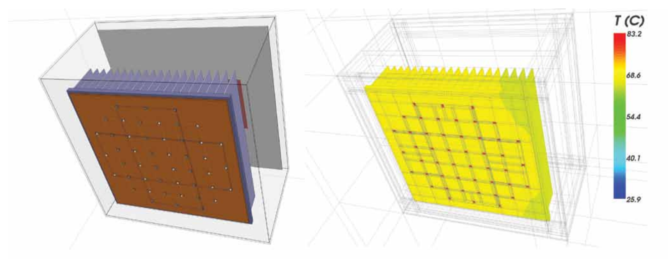


Figure 10. QLED thermal simulation of the low-bay light fixture

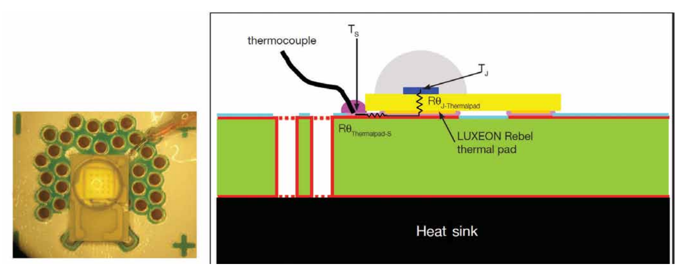


Figure 11. Thermocouple placement on solderability point of LUXEON Rebel

The calculation results from the thermocouple measurements closely match the QLED simulation results.

The thermal performance of the fixture was also analyzed at different drive current using QLED thermal simulation software. Table 3 below summarizes the results of these simulations:

Note: for these simulations TAMB= 25°C

Current (IF)	Junction Temperature (Tj)
350mA	87.5°C
500mA	111°C

Table 3. Results summary of QLED simulations

The results show that at a higher drive current, the junction temperature is still within an acceptable value for suitable LED operation to maintain performance and lifetime.

6. Power Solutions

A variety of power solutions were evaluated and leveraged to enable the Low Bay light application.

6.1. Modular Driver Solutions

The enclosure for the demonstration unit includes four AC-DC Advance Transformer 24V/0.7A drivers, shown in Figure 12, to operate the 48 LUXEON Rebel LEDs. Each driver connects to two parallel strings with six LEDs in series each. Two versions were included to accommodate regional input voltage differences, i.e. 120V and 230V version. The part numbers of the drivers used are as follows:

- 120V: LED-120A-0700C-24FO
- 230V: 9137-006-159

Figure 12. Advance Transformer AC-DC LED driver

Another modular driver solution option for the low-bay light is to use two 30W ROAL STRATO drivers, shown in Figure 13, (p/n: RSLD035-12) with an output current of 700mA and an output voltage of up to 42V, supporting 12 LEDs in series. The driver supports a wide range of input voltages (120, 230, 240, or 277 Vac), and has an efficiency of 90%.

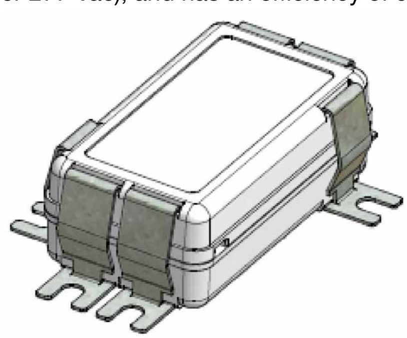


Figure 13. ROAL STRATO LED driver

6.2. IC-based Driver Solutions

The low-bay light can be connected to a single stage AC-DC or a dual stage AC-DC with DC-DC power solution.

The single stage AC-DC solution utilizes one SSL1750 driver by NXP. The SSL1750 has an integrated Power Factor Correction and is implemented as a flyback controller that can support a range of voltage supply from 70Vac to 276Vac. For the design, the SSL1750 solution outputs a constant voltage of 40V.

Alternatively, the SSL1750 driver can be connected to four LM3402 drivers by National Semiconductor. These drivers have an integrated N-channel MOSFET, a thermal shutdown protection, and supports voltages up to 42V. In the design, the LM3402 provides the constant current of 350mA to 12 LEDs in series. Therefore, 4 LM3402 driver solutions are required.

The two driver solutions are shown in Figure 14 below.

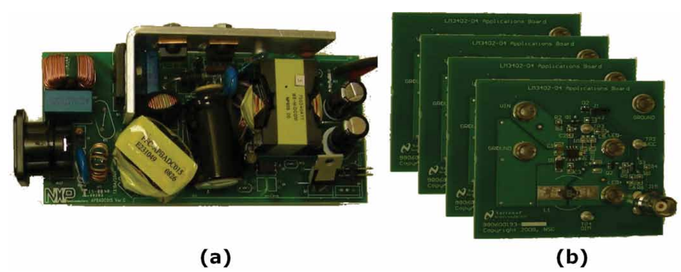


Figure 14. (a) NXP SSL1750 AC-DC driver, (b) 4 National LM3402 DC-DC drivers

7. Connectors

A connector system can be used with the low-bay light application to adapt to different design setups. The following are possible connector systems:

- **Tyco inverted thru board connector system**
  The inverted thru board connector system allows for conveniently placing all the connections from the underside of the board, as shown in Figure 15. This eliminates wire dress management issues and enables a low profile design. The part numbers for this connector system are:

i. Inverted thru board connectors: 2106091-1

ii. Inverted thru board mini CT plug assy.: 2058943-1

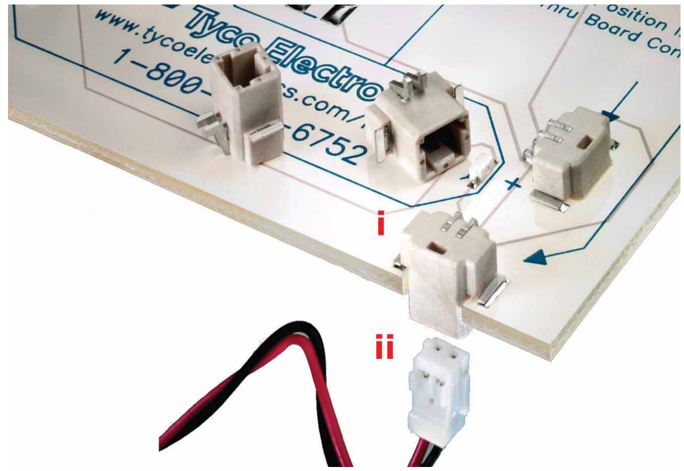


Figure 15. Tyco inverted thru board connector system

- **Tyco sealed connector system**
  The sealed connector system, shown in Figure 16, is a low profile, single row LED connector system that offers ingress protection up to and including immersion in 1 meter of water for 30 minutes (as per IP67). The part numbers for this connector system are:

i. Wire-to-board right angle header: 2106056

ii. Wire-to-board vertical header: 2106053

iii. Wire-to-wire receptacle contact: 2106123

iv. Wire-to-wire tab contact: 2106124

v. Plug assembly (for header, recept., tab): 2106135

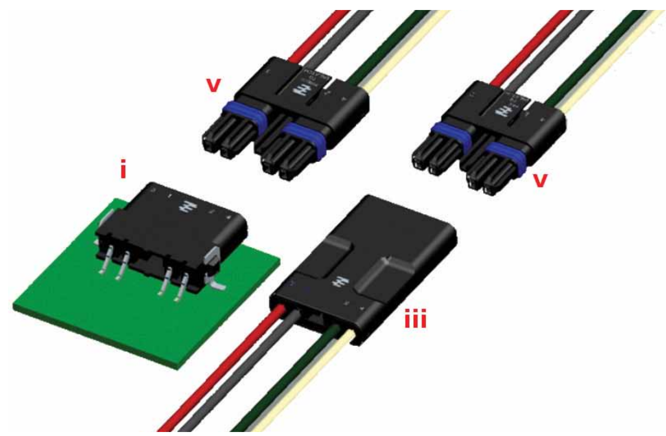


Figure 16. Tyco sealed connector system

- **AVX 9159 connector system**
  The AVX connector system, shown in Figure 17, offers board-to-board connectors for daisy chaining multiple LED boards together in series. The part numbers for this connector system are

i. Wired plug with latch: 11-9159-002-101-116

ii. Standard socket: 20-9159-002-101-116

iii. Standard plug: 10-9159-002-101-116

iv. Top loading socket: 22-9159-002-101-116

v. Shorting socket: 58-9159-002-000-006

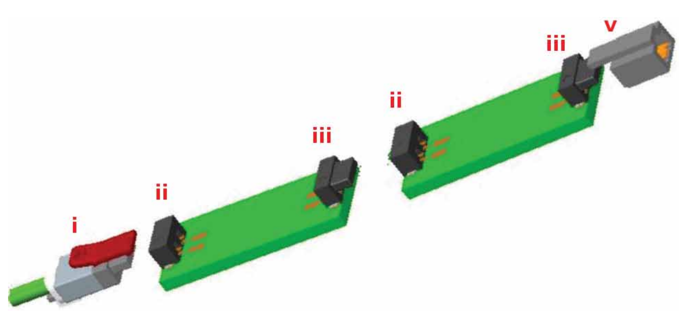


Figure 17. AVX 9159 connector system

8. Conclusion

The low-bay lighting system leveraging 48 LUXEON® Rebel LEDs developed by Future Lighting Solutions has proven to satisfy the requirements of light output, efficacy, and lifetime to enable lighting applications in the general lighting market.

The suggested optical, thermal, and power solutions are geared towards optimal performance and longevity of the LED-based system. Intelligent power solutions can be utilized to further enhance the capabilities of the LED-based low-bay lighting system with light and temperature sensing, emergency power backup and enabling wireless communications.

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