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Evacuation analysis of 1000+ seat Blended Wing Body aircraft configurations: Computer Simulations and Full-Scale Evacuation Experiment

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Abstract Blended Wing Body (BWB) aircraft with around 1000 passengers and crew are being proposed by aircraft manufacturers. This type of aircraft configuration is radically different from conventional tube type passenger aircraft and so it is essential to explore issues related to both fire and evacuation for these configurations. Due to both the large size and the unusual nature of the cabin layouts, computer simulation provides the ideal method to explore these issues. In this paper we describe the application of both fire and evacuation simulation to BWB cabin configurations. The validity of the computer evacaution simulations is also explored through full-scale evacuation experiments.

Introduction

Very Large Transport Aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. Capable of carrying more than 800 passengers, the A380 may be considered a VLTA however; it is nevertheless a conventional aircraft configuration and so falls within the realms of past operations and certification experience. The aviation industry’s drive for increased efficiency is leading to the consideration of less conventional designs and even greater passenger capacity, such as the Blended Wing Body (BWB or Flying Wing) passenger aircraft.

BWB designs being considered by the EC Framework 6 project NACRE (New Aircraft Concepts REsearch) are capable of carrying in excess of 1000 passengers on a single deck with 20 exits and eight longitudinal aisles. Furthermore, BWB layouts will mean that cabin crew at exits will not be able to assess the situation at opposite exit locations making redirection of passengers difficult. Indeed, the restricted and complex visual access and complex spatial connectivity offered by these aircraft configurations make wayfinding by passengers and redirection by cabin crew difficult and challenging. The industry standard evacuation certification regulations [1,2] require the aircraft manufacturer to demonstrate that the maximum complement of passengers and crew can be evacuated from the aircraft within 90 seconds through half the normally available exits. The BWB concept represents a significant departure from conventional aircraft design and as a result there are many challenging questions that need to be addressed. How long would it take to evacuate a BWB aircraft with around 1000 passengers and crew? How long would it take an external post-crash fire to develop non-survivable conditions within the cabin of a BWB aircraft? Is it possible for all the passengers to safely evacuate from a BWB cabin subjected to a post-crash fire?

These questions are explored in this paper through computer simulation and experimental analysis. As part of project NACRE, a specially modified version [3] of the airEXODUS aircraft evacuation model [4] was used to explore evacuation issues associated with BWB aircraft. In addition, a series of full-scale egress trials were conducted using a specially constructed BWB mock-up to verify key airEXODUS predictions. To simulate the fire, the SMARTFIRE [5] Computational Fluid Dynamics (CFD) software was used. Finally, the results from the fire simulation and the evacuation simulation were linked to investigate the evacuation in the presence of the developing fire. The results from these evacuation and fire simulations along with the results from the experiment are briefly presented in this paper.

airEXODUS and SMARTFIRE Simulation Models

The airEXODUS evacuation model is used to perform the evacuation simulations presented in this paper. airEXODUS [4,6] is designed for applications in the aviation industry including, aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation. Within the software, parameters such as aisle walking speeds, passenger exit hesitation times, exit opening times etc are derived from the industry standard certification trials. Cabin crewmembers can also be represented and require an additional set of attributes such as, range of effectiveness of vocal commands, assertiveness when physically handling passengers and the extent of their visual access within the cabin. The atmospheric conditions generated by the fire such as heat, radiation, smoke and toxic fire gases are derived from the SMARTFIRE CFD fire model [5]. The impact that these hazards have on the exposed population is determined using the Fractional Effective Dose (FED) and Fractional Irritant Concentration (*FIC*) concept [6,7]. These models consider the toxic, irritant and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2, low O_2, HCL, HBr, HF, SO_2, NO_2, Acrolein and Formaldehyde and estimates the time to incapacitation. Finally, when a passenger moves through a smoke filled environment their travel speed is reduced according to the experimental data of Jin [8]. To address issues associated with BWB cabin configurations, the airEXODUS evacuation model was modified in three specific areas:

- A novel scheme for passenger navigation was introduced based on wayfinding techniques used in the buildingEXODUS evacuation model.
- A modified model for passenger aisle swapping behaviour was introduced more appropriate for the BWB layout.
- A modified model to simulate cabin crew redirection procedures in BWB aircraft.

A research version of the SMARTFIRE V4.1 [5] software is used to perform the fire simulations in this study. The fire simulation model incorporated a range of sophisticated sub-models. A flame spread model including three ignition criteria [5] is used to generate gaseous fuel at the interior burnable surfaces. A toxicity model based on local equivalence ratio [9] is used to calculate the generation and spread of fire gases within the cabin. The calculation of smoke optical density utilises the mass optical density. Finally, the parallel version of SMARTFIRE is used to simulate the large-scale fire scenarios. The fire model has been validated by successfully reproducing the C133 fire test conducted by the US Federal Aviation Administration [10].

BWB Configuration

As part of project NACRE many BWB configurations were under investigation. In this paper we consider configuration FW1-1-1. The FW1-1-1 configuration is the base case from which all other NACRE BWB variants are generated. The FW1-1-1 configuration consists of 1020 passengers in a single class configuration, 25 cabin crew and 20 floor level Type-A exits (see Fig. 1). The exits on the left side of the aircraft are numbered L1, L2, up to L10 going anti-clockwise from from the front to the rear of the aircraft as shown in Fig. 1.

Evacuation Model Predictions

As airEXODUS is a stochastic model, the agents will not necessarily make the same decisions if the simulation is repeated, it is thus necessary to run the model several times for each scenario. For the results presented here, the model was run 10 times. The scenario considered here was a standard evacuation certification case where the exits on one side of the aircraft are considered unavailable. Thus of the 20 exits, 10 were made available on the left side of the aircraft. A standard opening time of 11.1 sec was used for each of the Type-A exits.

Also, note that the times specified in this paper refer to out of aircraft times and not on-ground times as exit slide configurations have not yet been determined. For the above scenario the out of aircraft times ranged from 80.6 sec to 92.8 sec with an average of 85.9 sec. While the minimum and average egress times are well under 90 sec, we note that the maximum evacuation time is some 3 sec over the maximum permitted time. It should also be recalled that these times represent out of aircraft times and not on ground times which may be some 3 sec longer.

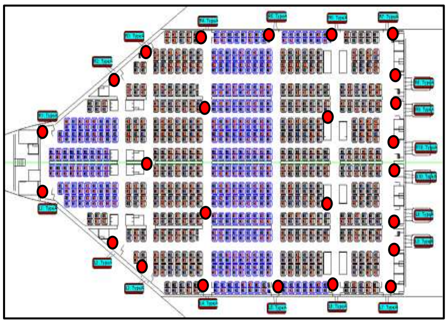

Fig. 1. Cabin layout for FW1-1-1 showing location of cabin crew (circles) and exits (blue rectangles)

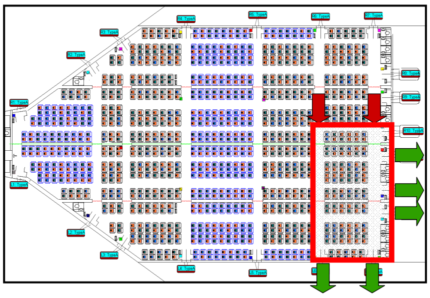

Fig. 2. Section of full-scale cabin represented within the experimental mock-up

From the predicted exit usage results (see Fig. 3) it is evident that the exits located at the south east corner of the cabin experience very low passenger usage. The worst offenders are the corner exits L7 and L8 with an average of 30 and 56 passengers using these exits respectively (i.e. the two exits in the bottom right corner of Fig. 1). The passenger exit usage results also indicate that exits L2, L3, L4 and to a lesser extend L5 are over-utilised. There is a clear trend that the exit capacity in the rear corner of the cabin cannot be fully utilised. This is thought to be for several reasons, firstly, to utilise L7 and L8 requires passengers to by-pass other functioning exits. Secondly, the location of these exits in the corner of the cabin means that they have a small natural catchment area of passengers for which these exits are their closest exits. Finally, the physical location in the corner provides poor visual access within the cabin. As a result it is difficult to reduce the heavy congestion in cross aisles 2-5 and the heavy usage of the forward exits (i.e. L2 to L6). If we consider the ratio of the time wasted in congestion to the time spent in evacuating we find that in the average simulation, passengers spend on average 40% of their personal travel time caught in congestion. This indicates that a significant amount of time is lost to congestion in this scenario.

This trend in exit usage has been observed in all of the numerical predications for the various configurations examined. While the results appear to be consistent and plausible, it was not clear if this was an artefact of the numerical simulation or if it was a realistic result. In particular it was not clear if the crew redirection model and the passenger navigation model were producing realistic predictions. To investigate this further it was necessary to undertake experimental evacuation trials.

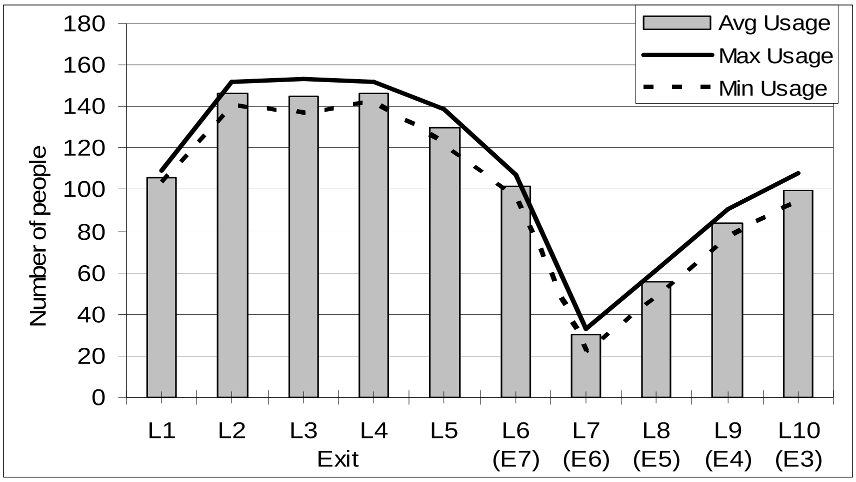

Fig. 3. Predicted average exit usage for the 10 exits, L1 to L10.

Large Scale Evacuation Trials

The purpose of the experimental programme of work was to observe and quantify the evacuation behaviour and performance of passengers and crew in novel BWB configurations and validate the computer simulations. Conducting full-scale trials involving over 1000 people was prohibitively expensive and impractical and so it was decided to undertake full-scale trials using a portion of the BWB cabin. Furthermore, given the concern over the modelling of the rear part of the cabin, the trials focused on this part of the cabin (see Fig.2). The key issue of interest was identifying whether participants would redirect and bypass a usable exit while trying to evacuate. To accurately represent this behaviour within the mock-up it was estimated that 380 people would need to be utilised in the mock-up of this area. Note that in order to measure whether occupants are willing to bypass a usable exit there was no need to have all the test subjects seated within the mock-up. In total some 88 participants would be seated in the mock-up and 146 participants would be brought into the mock-up via the two cross aisles feeding the mock-up section (see Fig.2).

The cabin mock-up was constructed at Cranfield University who also recruited the trial participants under contract to the University of Greenwich. A series of four trials were conducted over two days with two groups of participants, 375 participants on the first day and 358 participants on the second day. Trials considered full and partial partitions, additional crew and a repeat of the full partition trial. The participants were aged between 20 and 50 and each cohort of participants was used in all four trials on each day. Data from the trials was collected using some 12 internal fixed mounted cameras (see Fig. 4) and five external fixed mounted cameras. It is important to note that the trials were conducted in non-competitive conditions similar to those found in certification trials. Only the results from trial 1 session 1 are discussed here (trial with full partitions) however, these results are indicative of the findings from all the trials.

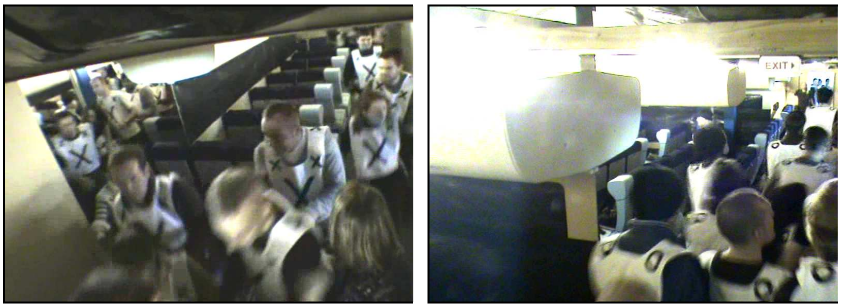

Fig. 4. View from Cameras 9 and 12 during Trial 1 Session 1

In comparing the exit locations used in the full-scale aircraft (and in the computer model) with those in the experimental mock-up, the designation L1 – L10 are used to represent the exits on the left side of the aircraft. In the mock-up, an E designation is used to describe the exits in the experiment. The link between the exits used in the experimental mock-up and simulation is as follows: L6 – E7, L7 – E6, L8 – E5, L9 – E4, L10 – E3 (see Fig.2).

A significant observation to emerge from the trials is that the exit usage distribution predicted by the airEXODUS software (see Fig.3) is reflected in the results found in the experimental trial (see Fig. 5). In particular, the corner exit E6 (L7) is the most underutilised exit while the first back exit that the participants encounter, E3 (L10) is heavily used. There is a gradual decline in the number of people using the next exits along (E4 (L9) and E5 (L8)) culminating in the minimum exit usage for E6 (L7) in the corner. The number of people using the next exit (E7 (L6)) then increases significantly. It should be noted that the modelling results depicted in Fig. 5 represent an average over 10 simulations while the experimental trial results represent the observations from a single trial. There is expected to be significant variation in exit usage for repeat trials which is not reflected in the trial results. This explains some of the differences between the predicted and measured exit usage values. It should also be noted that in the simulations there is a supply of passengers along the longitudinal aisles closest to the L6 (E7) exit that will also feed the exit. This will also contribute to the slighter higher number of people predicted to use the L6 (E7) exit.

The exit by-pass that was noted in the trials is also of interest. If we consider the stream of people coming down the cross aisle closest to the rear three exits (145 participants) we note that 39.3% by-passed the first exit (E3), 6.9% by-passed the second exit (E4), 2.1% by-passed the third exit (E5) and no one by-passed the forth exit (E6). In comparison, airEXODUS predicts that 41.0% of the passengers will by-pass the first exit which is in good agreement with the experimental findings.

We note that while just over a third of the participants are prepared to by-pass one exit, very few will by-pass more than one exit.

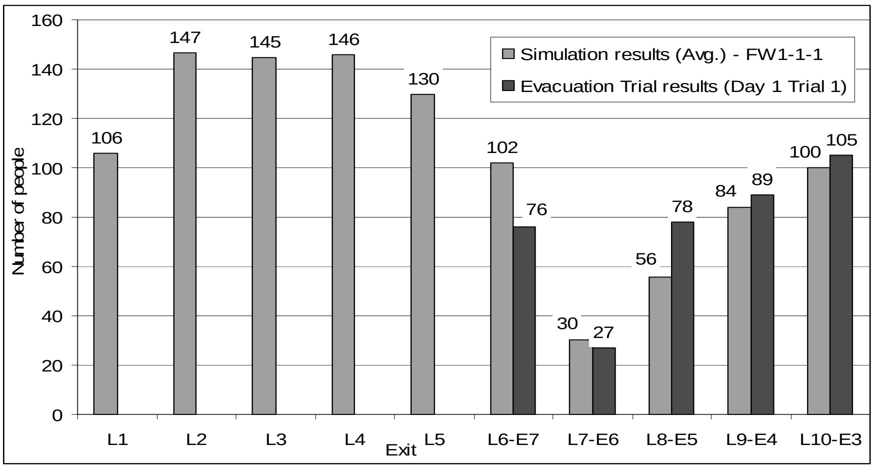

Fig. 5. Comparison of exit usage between modelling predictions for full cabin and experimental results for cabin section.

Fire Model Predictions

In a post-crash aircraft fire, the fire is typically initiated outside the cabin usually due to a fuel spill. The fire then attacks the aircraft cabin gaining entry via ruptures to the fuselage due to impact damage, or burn through and ignites the interior materials. In the NACRE simulations, the external fuel fire source is located on the right side of the aircraft. Six different fire scenarios were investigated, all of which involved opened exits on the left side of the cabin during the entire fire simulation. Here we report the results of Scenario 3, with the wide cabin rupture, equivalent to three Type-A exits. The external fire had dimensions of 5.2 m long by 2.5 m wide and the fire reached a maximum heat release rate of 18 MW after 8 sec and burnt at this maximum rate for 10 minutes. The computational mesh used for the NACRE simulations consisted of approximately 650,000 cells. A parallel cluster consisting of seven processors was used for the simulations. This reduced the run time from 425 hours on a single processor to around 70 hours for a single 480 second fire simulation.

At flashover, the fire very rapidly changes from being localised to engulfing the entire volume. An important outcome of this analysis is that flashover is not observed within the first 480 sec, which is much longer than the certification requirement of 90 sec. The combustion behaviours over the entire simulation time do not display the rapid increase in values, which is the hallmark of flashover.

The seats close to the fuel fire are the first cabin fixture to be ignited. Later, the fire spreads to portions of the seats in front of and just behind the initially ignited seats. At 480 seconds, the fire mainly remains localised and confined to seats and overhead materials in the vicinity of the rupture. Clearly flashover is not the factor that will drive survivability in this type of scenario. Predicted (interior) HHRs reach a local maximum at approximately 60 sec. At 60 sec, severe fire hazards are mainly confined within the immediate vicinity of the rupture at head height (1.7 m above the floor). Within the lower layer (0.5 m above the floor), fire hazards such as temperatures and toxic gas concentrations are at very low levels in the vicinity of the rupture however, radiation fluxes are at untenable levels. After 80 sec the hot fire gases have spread throughout the cabin section closest to the rupture. Temperatures at head height are around 100^{O}C through most of the section. Hot fire gases begin to spill into the next cabin section with temperatures around 60^{O}C in parts of the third longitudinal aisle. The atmospheric conditions in most of the cabin at around 90 seconds appear to be survivable. Only conditions in the cabin section immediately adjacent to the rupture pose a threat to life.

In order to analyse the likely impact of fire hazards on the evacuating passengers, the NACRE cabin is divided into 67 zones for data output from the fire simulations. The fire hazard data in the upper layer (1.5 m to 2 m) and lower layer (0.3 m to 0.8 m) within each zone is a weighted average of variable values of all cells within the layer. This data at each time step is then exported to airEXODUS and used in the evacuation simulation, exposing the population to the evolving fire hazards. Presented in Fig. 6 are the predicted radiation fluxes at Zone 2 and 61. Zone 2 is in the section of longitudinal aisle immediately opposite the cabin rupture and hence the external fuel fire while Zone 61 is in the section of cross aisle adjacent to exit L4 on the opposite side of the cabin to the fire. As seen in Fig.6, the radiation fluxes in both the upper and lower layers of Zone 2 reach hazardous levels of 10 kW/m^2 just before 10 sec. The local CO concentrations peak at approximately at 60 sec, which is 50 sec after the radiation flux reaches critical values. This demonstrates that in the vicinity of the rupture, radiative flux is the key threat to survivability in Zone 2. In Zone 61 we note that the radiative fluxes and CO values are near ambient values up to 90 sec after ignition and pose no threat to the passengers. The same conditions exist in the zone opposite L5. Thus conditions at two heavily used exits pose no threat to the passengers.

As with the case without fire, the evacuation simulation was run 10 times. This produced an average evacuation time of 89.3 sec compared with 85.9 sec without the fire. This modest increase in evacuation time is due to the presence of smoke within the cabin which reduces visibility and reduces travel speeds. While there is only a modest increase in evacuation times there are 12 predicted fatalities in this simulation. All 12 fatalities occur in the immediate vicinity of the rupture and all the fatalities are a result of exposure to radiative heat. The fatalities occur between 8 and 34 secs from the start of the simulation, with three fatalities occurring within the starting location and nine fatalities occurring in the aisle adjacent to the starting location. Given these conditions, it is felt that these fatalities are unavoidable, given their starting location and proximity to the fire.

In addition to the predicted fatalities, some 25 passengers are predicted to be injured due to heat exposure. Of these, 3 passengers are considered to have serious life threatening injuries. None of the survivors suffers from serious exposure to the toxic fire gases however, most of the survivors suffer from light exposure to HCl.

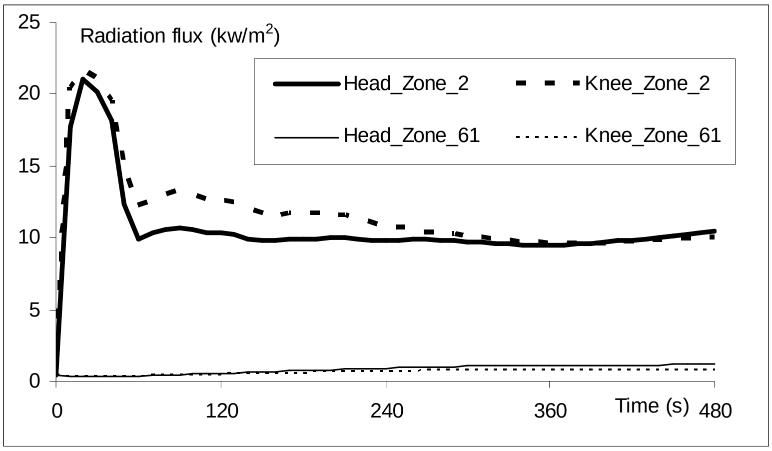

Fig. 6. Predicted radiation fluxes in Zone 2 and 61

CONCLUSIONS

The airEXODUS evacuation simulation suggests that the NACRE BWB with 1045 passengers and crew can be evacuated within 80.6 sec to 92.8 sec with an average of 85.9 sec. Improved performance can be expected by better utilisation of the rear, and in particular the corner cabin exits. This may be achieved through improved passenger familiarisation with the cabin layout and improved visual access. However these times represent out of aircraft time and not the on-ground time as required by current regulation.

Experimental data from full-scale evacuation trials support the appropriateness of the passenger exit selection behaviour implemented within the airEXODUS evacuation model and suggest that it is suitable for these types of applications. The experimental trials also support the overall findings of the numerical simulations. The experimental results highlight the importance of situational awareness and visibility in navigating a successful exit path within the complex layout of the BWB. Improving the passenger’s knowledge of the cabin layout and the location of the exits and providing them with good visual access of the exits and aisles will be essential in achieving an efficient evacuation of complex BWB configurations.

Fire simulations suggest that the BWB cabin exposed to an 18 MW post-crash external fuel fire via a large cabin rupture does not flashover within the first 480 sec. This suggests that, unlike conventional tube style aircraft, flashover is not the primary factor driving passenger survivability. When the SMARTFIRE fire simulations are linked to the airEXODUS evacuation simulation, thereby exposing passengers to the developing fire, the average evacuation time increases to 89.3 sec. In addition, some 12 fatalities and 3 serious injuries are predicted. All the fatalities and injuries are the result of exposure to radiative heat and all are initially located in the immediate vicinity of the rupture. Smoke and toxic gases are not considered a serious threat in these scenarios. Given the location of the fatalities and the severity of the fire conditions, it is felt that these fatalities are unavoidable and are not inherently due to the cabin architecture.

Ultimately, the practical limits on passenger capacity and aircraft design are not based on technological constraints concerned with aircraft aerodynamics but on the ability to evacuate the entire complement of passengers and crew within agreed safety criteria. This work has demonstrated that the NACRE BWB configuration has the potential of satisfying such safety criteria and is arguably capable of providing an equivalent or better level of safety to today's conventional aircraft.

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